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Prepared for
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1.0 SUMMARY

Need for substantial improvements in the efficiency of both the air traffic control (ATC) system and airplane operations is underscored by the recent undertaking of the FAA to renovate the ATC system over the next 10 years. National Airspace System (NAS) plan goals include providing system capacity to meet predicted demand, increasing fuel efficiency of operations, and increasing air traffic controller and flight specialist productivity. The basis for the increased operational efficiency in the plan is the increased level of automation expected, together with the consolidation of facilities and standardization of systems. In the introduction to the NAS plan (ref. 1) there is recognized a need for "a total system approach—flexible enough to: accommodate future demands and technology; improve vital safety services; increase productivity; constrain costs; reduce the Federal role; allow for a rational system evolution; and recognize the user's desires for minimal restrictions on the use of the airspace."

Significant potential exists to improve both ATC and airplane operations (minimum fuel flightpaths, increased ATC/airport capacity, reduced delay, and reduced pilot and controller workload) by developing avionics specifically for operating in the evolving ATC system. The NASA Advanced Transport Operating Systems program and Transportation Systems Research Vehicle (TSRV) B-737 experimental system provide a unique environment for these avionics developments.

Recently, the FAA has implemented the national program of En Route Metering (ERM) in which arriving traffic is metered into the terminal area by assigning metering fix times to each flight. The FAA is also accomplishing research and development on more advanced flow management concepts which are critical elements of the NAS plan. These concepts involve time-based (4D) control (e.g., en route metering and automated en route ATC). These FAA flow management concepts assume controlling aircraft to the desired time-based track by issuing tactical commands from the ground.

Such time-based navigation could also be an airborne function which has potential to assist and complement FAA flow management concepts. Referred to as time navigation (TNAV), RTCA Special Committee 137 has defined it as, ". . . a function of RNAV equipment that provides the capability to arrive/depart at a specified waypoint at a specified time. Called 4D when added to a 3D system" (ref. 2). The TNAV equipage study reported in this document evaluates the impact. The method of study employed the use of a fast-time multiple-airplane simulation, the flow management evaluation model, representing operation of ERM at an example airport.

The flow management evaluation model simulates the operating environment of an air route traffic control center. Airspace structure, weather conditions, traffic characteristics, ATC rules and procedures, flow management algorithms, and airplane performance data are required inputs. The model represents interaction of the ATC system with each aircraft flying in the airspace. It provides scheduling, routing, controller clearance generation, conflict checking, and aircraft trajectory generation processes. The model outputs statistical summary data (capacity, delays, fuel used, conflicts, clearances), flight histories, and plot options.

The model has been used to simulate the effect of mixed TNAV-equipped and unequipped aircraft operating in the En Route Metering environment. This study of TNAV equipage is based on a limited sampling of the future ATC environment, but provides positive results of the introduction of airborne-based time-at-waypoint control using the capabilities of advanced flight management systems (FMSs). Impact is assessed primarily in terms of user efficiency and an ATC workload indicator (numbers of conflicts and of metering clearances). Basic conclusions based on this study indicate: (1) confirmation of previous fuel savings estimates for equipped users, (2) a decrease in conflicts between 25% and full equipage, (3) a decrease in metering clearances with increasing equipage, and (4) demonstration of significant probability that TNAV clearances can be obtained even at low equipage levels. Thus operators could start realizing fuel savings even before widespread availability and use of onboard TNAV. Probability of TNAV clearance becomes greater with increased equipage.

The next step required in the integration of TNAV avionics into the ERM ATC system is development of real-time simulation studies and planning of flight tests and operational demonstrations of experimental TNAV systems which can operate in the advanced ATC environment to verify operational efficiencies which have been indicated in this simulation study.

2.0 INTRODUCTION

The NASA Advanced Transport Operating Systems (ATOPS) Flow Management Avionics Research Studies program has examined requirements for operating in the current FAA time-based en route metering system (ref. 3). General and interim path definition algorithms have been developed and the interim algorithm tested in simulation and flight. Figure 1 summarizes the approach used in the flow management system studies.

The FAA has several advanced flow management concepts under study or development. These include en route metering, automated en route ATC and integrated flow control of traffic management system. These concepts are basic elements of the National Airspace System plan providing transition from today's time-based en route metering to the 1990-2000 ATC system.

Definition of some alternative flow management concepts, development of scenarios for ATOPS application, analysis, and recommendation of further testing of scenarios was accomplished (NAS1-14880 TRA-112). Additional work to be accomplished was defined by NASA Task Requirement A-2 under contract NAS1-16300. During this current task, a fast-time simulation was used to evaluate flow management systems and algorithms representing their operation in a multiple airplane demand environment. These algorithms and scenarios have been used to conduct this simulation study of the introduction of time navigation (TNAV) equipped aircraft into the ATC system.

This report of flow management systems requirements and potential benefits also contains a description of the flow management evaluation model including the En Route Metering algorithms employed (in sec. 5.0 and appendices A and B). The original study plan was to evaluate both the Local Flow Management/Profile Descent (LFM/PD) algorithm and the En Route Metering with Metering and Spacing (M&S) system algorithm in the study. Evolution of the near-term ATC metering programs into En Route Metering (ERM) has prompted its substitution in the study as the baseline flow management concept.

3.0 SYMBOLS AND ABBREVIATIONS

A/C	aircraft
AAI	aircraft arrival interval
AAR	airport acceptance rate
ACLT	actual calculated landing time
ARTCC	air route traffic control center
ATC	air traffic control
ATOPS	Advanced Transport Operating Systems
BOD	bottom of descent
CAS	calibrated airspeed
C_D	coefficient of drag
CLT	calculated landing time
CTA	calculated time of arrival
DEN	Denver
EPR	engine pressure ratio
ERM	En Route Metering
ETA	estimated time of arrival
FCDI	flow control display interval
FCLT	freeze calculated landing time
FMEM	Flow Management Evaluation Model
FMS	flight management system
FTUI	flowtime update interval
4D	four dimensional
ISA	international standard atmosphere

kcas	knots calibrated airspeed
LFM/PD	Local Flow Management/Profile Descent
LRC	long-range cruise
M&S	Metering and Spacing
MFT	meter-fix time
MLDI	meter list display interval
NALT	next available landing time
NAS	National Airspace System
NASA	National Aeronautical and Space Administration
OAG	Official Airline Guide
OFN	outer fix name
OFT	outer fix time
QRE	Quick Reference Edition
RH	random (unscheduled) high-performance aircraft
RL	random (unscheduled) low-performance aircraft
SLDI	sector list drop interval
σ	standard deviation
TAT	total air temperature
TCLT	tentative calulated landing time
TCV	Terminal Configured Vehicle
TMA	terminal area
TNAV	time navigation
TOD	top of descent
TSFC	thrust specific fuel consumption

TSRV	Transport Systems Research Vehicle
3D	three dimensional
VMO	maximum operating velocity
VTA	vertex time of arrival

4.0 EN ROUTE METERING — CONCEPT OVERVIEW

This section of the document describes development of the concept of arrival metering, defines basic metering functions, details implementation of metering in the Denver ARTCC, and describes those "enhancements" of arrival metering such as internal and expanded metering which have been developed.

4.1 DEVELOPMENT OF THE CONCEPT OF EN ROUTE METERING

On November 15, 1976, the FAA issued the Local Flow Traffic Management National Order, 7110.71. The purpose was to establish "a local flow traffic management program designed to enhance safety, conserve aviation fuel, and reduce the impact of aircraft noise on the local communities." The order directed air traffic divisions, air route traffic control centers (ARTCCs), and air traffic terminal facilities to review and revise procedures to reduce flying time at low altitude (below 10,000 ft) and provide for the maximum use of profile descents from cruising altitudes to the approach gate.

The order, in addition, established a metering program to develop procedures to monitor the arrival flow to determine when the number of aircraft approaches system capacity. Traffic shall then be metered so as not to exceed this capacity. When delays are imposed, the priority of landing shall be based on the calculated time of arrival (CTA) for each aircraft. CTAs shall be calculated based on the estimated time of arrival at the meter fix plus the estimated flying time to the runway. These times shall then be adjusted to resolve simultaneous demands at the airport and to establish the time that an arrival aircraft will be required to cross the meter fix.

Profile descent procedures were published at Denver, Dallas, Atlanta, St. Louis, Los Angeles, Miami, and San Francisco. Time-based arrival metering programs were implemented at the Denver and Fort Worth centers.

The term "arrival metering" as used here describes a system of matching demand on an airport to that airport's capacity by using time control at meter fixes. This system's initial prototype was implemented at Fort Worth ARTCC to feed Dallas-Fort Worth International airport. This initial application was called "Dallas flow control." FAA order ZFW 7110.132, "Flow Control Procedures," documents the Fort Worth ARTCC system.

Denver ARTCC was selected as the testbed for the national program. Denver has now implemented the system (with profile descents) and an automated version has been developed and is operational at both centers. This automated version provides the techniques to be implemented in other ARTCCs. Their procedure is embodied in order ZDV 7110.51, "Metering and Profile Descent Procedures," February 24, 1977.

In addition to the FAA order, Advisory Circular 90-73, January 13, 1977, was published to familiarize pilots with the new procedures. Beyond these metering programs the FAA planned for the installation of automated arrival metering at all centers. The flow management order essentially directed all ARTCCs to prepare plans for implementing local flow management at all airports where high performance aircraft operate, within a 20-month period. Sixteen busy airports were to be implemented within 12 months with the balance on a more relaxed schedule.

In addition, the order directed that the system accommodate "profile descents," which are a separate but closely related technique to be used in conjunction with arrival metering.

Although the schedule outlined in the order was not met, development of automation software has been completed at Denver and Fort Worth as an extension of the NAS En Route Stage A program. The metering function has been integrated into NAS Stage A software and was delivered to all centers in mid-1982. As of early 1985, en route arrival metering has been operational at six centers: Denver, Fort Worth, St. Louis, Minneapolis, Seattle, and Atlanta.

Enhancements to En Route Arrival Metering are expected in 1987. These include intercenter, multiple airport, and outer fix metering. In addition, the FAA is searching for significant improvement of existing system flow control functions in its ongoing Traffic Management System Program. These efforts together with investigations of how to take advantage of onboard flight management technology are intended to provide the basis for evolution from today's En Route Arrival Metering to the more automated ATC flow management system of the 1990-2000 time frame.

4.2 EN ROUTE METERING FUNCTIONS

The arrival metering strategy is to predict the time each airplane will arrive at the runway if no control is exercised. This is accomplished dynamically while airplanes are still at cruise altitude and perhaps 150 to 175 nmi from the meter fix.

Based on this initial arrival time estimate, a desired runway (or airport) schedule is created which provides for interoperation times consistent with airport capacity and which resolves conflicting runway use. Thus a desired time slot (runway schedule) is created for each airplane perhaps 30 min before the operation is to occur. This list of assigned runway times is then adjusted by the transition times from the meter fixes to the runway to determine an assigned time at the meter fix. It is this assigned meter-fix time which the en route sector controller will use to deliver each airplane to the TRACON. The controller uses speed control, vectoring, and holding as needed to achieve the delivery with an accuracy goal of ± 1 min (ref. 4). He may, if necessary, interchange or "swap" the times assigned to two aircraft as flow rate is the primary parameter. In addition to metering arrivals, the controller must provide adequate separation between successive arrivals. Without considerable metering experience, controllers have difficulty achieving the time accuracy goal, according to ARTCC personnel.

Figure 2 is a block diagram of the arrival metering procedure. ARTCCs have instituted a control position called the arrival sequence control. This position is involved with the sequencing and scheduling of airplanes rather than the actual control, which is eventually accomplished by the sector controller who is feeding the meter fix. The arrival sequence controller works with computer-generated "flight strips" which indicate aircraft identification, type, the arrival meter fix and the estimated arrival time at the meter fix. In the original implementation, estimated meter-fix time was generated by projecting the airplane from its current position to the meter fix at the present groundspeed from the Stage A tracking algorithm. A nominal terminal area (TMA) transition time value was added to the meter fix estimate to obtain the estimated landing time. TMA transition times were based on a table of values which gives the time as a function of the particular meter fix and airplane type category. In addition, corrections to the meter-fix time estimate could be given to the arrival sequence controller by the computer based on changing events.

Current automation software (ERM-1) employs an "adaptation package" to specify geometry/procedures/traffic data specific to a given terminal area. Approach times are now calculated based on specification of a sequence of approach legs. Such an approach leg is described in terms of path distance, heading, altitude, and true airspeed (which may also depend on aircraft type). The impact of wind on flight leg transition time is also considered by entering forecast/measured wind values. Each arrival is assigned a nominal approach path consisting of a sequence of approach legs for computing the estimated TMA transition time.

In a "passive metering" mode, the arrival sequence controller reviews the list of landing times to identify (1) whether the airport capacity will be exceeded for any 10-min period and if so, (2) to see if any landing conflicts will occur. When the average aircraft delay exceeds a threshold during the 10-min interval, control progresses from "passive metering" to "active metering" by utilizing ERM-1 software. The metering program determines successive landing time slots for each airplane based on the sequence established by the initial landing time estimate and an interoperation landing interval based on current airport acceptance rate. These assigned landing times are then readjusted for the nominal TMA transition times to obtain an assigned time at the designated meter fix for each airplane. This assigned meter-fix time (MFT) is then displayed to the appropriate sector controller who will control the airplanes to make good the assigned time. Figure 3 shows a typical meter list for Denver arrivals onto runway 26. Arrivals are separated into a "nonfreeze" and a "freeze" list. Those arrivals within 13 to 15 min of their MFT have had their scheduled runway times "frozen." They are listed separately from other aircraft whose scheduled runway times are recomputed based on updated ETAs. Alternate runway configurations and flow rates can be specified to reflect changing operating conditions.

This process (1) only allows airplanes for which a landing time has been computed into the near-terminal area, (2) equitably distributes ATC delay, and (3) indicates when and how much holding will be required in the en route area. The automation program provides algorithms to perform the runway time calculation, runway scheduling, and meter-fix time assignment functions, with results displayed at the arrival sequence controller position, and to the appropriate sector controllers when active metering is in progress.

4.3 DENVER CENTER EN ROUTE METERING IMPLEMENTATION

The arrival metering function estimates flying time to the runway before arriving aircraft reach the ARTCC boundary. For the Denver Center implementation this occurs nominally 20 flying minutes before reaching the Denver Center boundary. A metering parameter, the flow control display interval (FCDI), establishes this metering processing initiation time.

Figure 4 shows the basic high-altitude route structure for aircraft originating outside the Denver Center airspace and flying to Denver Stapleton. The five circles in the center of the figure represent the four Denver meter fixes and Stapleton Airport. Meter fixes are time control waypoints associated with the metering process. They also mark the transition from the Center (en route) control authority to Denver tower control. All high-altitude routes "feeding" the Denver airport are merged into four approach streams before they reach the meter fixes. A typical freeze boundary is also indicated in the figure. Required delay absorption is carried out by arrival metering (with exceptions detailed in the next section) between the freeze boundary and the meter fixes.

Inside the meter fixes the nominal approach geometry is indicated in Figure 5 for Denver Stapleton runway 26. The figure also indicates transfer of control points (center to tower) for low-performance aircraft. These approach paths are represented in the arrival metering calculation process by the runway adaptation data (illustrated in fig. 6).

4.4 EN ROUTE METERING ENHANCEMENTS

In addition to the standard arrival metering functions performed at the Denver ARTCC as previously defined, additional capabilities have been used including (1) internal metering, (2) expanded metering, and (3) quota flows. Each of these programs is summarized below. Use relative to current airport level of delay is indicated in Figure 7.

Internal metering is initiated when delays at Denver Stapleton are 3 min or more. All aircraft originating within Denver Center airspace are eligible. The internal metering procedure allows the airplane to absorb most of its scheduled arrival delay on the ground prior to departure. The procedure is not mandatory. All internally metered aircraft have their landing time slots reserved.

Expanded metering was operated at Denver Stapleton when arrival delays were projected to exceed 30 min. Departures from airports in Salt Lake City Center, Albuquerque Center, and Minneapolis Center's area that are nonstop and within 75-min flying time of Stapleton were eligible for the Denver Center expanded metering program. Departing aircraft were given the option of taking a ground delay to avoid an airborne delay at Denver. Takeoff times allowed 10 min for maneuvering to ensure meeting the reserved meter-fix time at Denver. Aircraft could depart earlier than the suggested departure time; however, aircraft that arrived late lost their reserved landing times and were rescheduled for arrival approximately one hour later.

Quota flow is a method of restricting the number of aircraft which may enter the Denver Center's airspace in any given hour. The quota will normally be equal to the airport acceptance rate at the arrival terminal. Quota flow is usually implemented when arrival delays exceed 30 min and the number of aircraft being held equals one hour's acceptance rate. For example, if the airport acceptance rate is 30, delays are 35 min, and 32 aircraft are holding, Central Flow Control may implement quota flow of 30 to 35 per hour for Denver Center, including internal departures. The ERM System has no knowledge of delays incurred on the ground outside the Denver Center area nor in the air in an adjacent center's airspace, so these delays are not accounted for nor credited. As a consequence, an aircraft en route to Denver could conceivably incur an hour delay in the Kansas City Center area and, subsequently, incur another one-hour delay in the Denver Center area in addition to any ground delay taken at the departure point.

5.0 A MODEL OF THE DENVER CENTER OPERATIONS

In order to evaluate proposed changes in operation with the introduction of TNAV (4D RNAV) equipment into an en route arrival metering environment, the Boeing-developed Flow Management Evaluation Model was applied to the Denver ARTCC with ERM-1. A brief description of this model of Denver Center ERM operations follows. A data dictionary and a route data base are contained in appendices A and B, respectively.

The Flow Management Evaluation Model (FMEM) is a fast-time, multiple-airplane simulation. It processes a list of aircraft from a traffic preprocessor (produced offline prior to the simulation execution). The model proceeds in fixed time steps updating ATC arrival metering and aircraft profile processing. Statistics are collected over specified time intervals to use in evaluating the efficiency of operation. Model inputs include airspace structure, weather conditions, traffic characteristics, ATC rules and procedures, flow management parameters, and an aeroperformance data base. The model simulates interaction of the ATC system with individual aircraft flying in the Denver Center airspace. It provides routing, scheduling, controller clearance generation, conflict checking, and aircraft trajectory generation processes. The model outputs include statistical summary data, flight histories, and plot options for selected operations. A top-level structure chart is shown in Figure 8.

The primary model modules are the traffic preprocessor, the flow management simulation, and the flight histories analysis. The simulation comprises ATC processing, en route metering functions, and the profile generation algorithm.

The traffic preprocessor creates the traffic demand entering the ARTCC. The traffic includes (1) scheduled commercial jets, (2) scheduled commuter, (3) random high-performance aircraft, and (4) random low-performance aircraft, as illustrated in Figure 9. The demand list, which is the output of the preprocessor, is a compilation of all airplanes entering the simulation at defined entry points. Airplanes are ordered according to entry point crossing times. These times, as well as other initial conditions and trip information, are derived from appropriate published traffic schedules, route structures, airport delay data, and airplane characteristics. A portion of the demand list for Denver Center for August 1980 is shown in Figure 10. Note that Boeing equivalents to other manufacturers' aircraft types were used due to the unavailability of performance data for non-Boeing types.

The air traffic control module of the simulation keeps track of all "active" aircraft in the simulation, assigns routings, determines present position (radar) data, and monitors conflicts (fig. 11). Ground hold processing (fig. 12) is also performed by the ATC module. The ATC module also simulates actions of the controllers in assigning speeds, vectors, or holding to achieve meter-fix times (fig. 13).

The arrival metering module (fig. 14) simulates current automation software as installed in the NAS Stage A system (ref. 5). Functions performed by the arrival metering software are summarized in Section 4.2. These include (1) runway arrival time prediction, (2) runway sequencing and scheduling, (3) delay determination, and (4) creation of meter and freeze lists.

The profile generation module (fig. 15) provides aircraft trajectories based on point mass, steady-state equations of motion. A performance data base is employed for the various

"commercial jet" aircraft types modeled, including thrust, drag, fuel flow, and speed envelope data. These trajectories represent the "true" positions of aircraft in the simulation. They are generated for initial aircraft entry into the simulation based on target plan data and in response to ATC clearances. Flight profiles are computed for "unequipped" aircraft in response to controller speed, vectoring, or holding clearances and for TNAV equipped aircraft in response to meter-fix time clearances based on en route metering algorithms. Scheduled commuters and random high-performance descent paths are simulated using nominal 3-deg descents.

The FMEM provides data on flow rates and capacity, level-of-delay, fleet fuel burn, controller workload (in terms of number of clearances generated), and safety (in terms of numbers of conflicts). Outputs are accumulated, processed, and formatted in the flight histories analysis module. Further descriptions of the traffic preprocessor, ATC, arrival metering, and profile generation processing follow.

5.1 THE DENVER TRAFFIC DEMAND MODEL

Traffic for the flow management simulation is created in the traffic preprocessor. Traffic includes both scheduled and randomly introduced aircraft. The demand list, which is the output of the traffic preprocessor, is a compilation of all airplanes entering the simulation at defined entry points. Airplanes are sequenced according to entry point crossing times. These times, as well as other initial conditions and trip information, are derived from appropriate published traffic schedules, route structures, airport delay data, and airplane characteristics.

Denver Center airspace is depicted in Figure 4. Subject to satisfaction of certain eligibility requirements, flights originating outside Center airspace are initially processed by the Denver metering program approximately 20 min prior to entering Center airspace. Thus, under nominal conditions of Mach .78 at 35,000 ft, arrivals are entered into the metering program roughly 150 mi outside the Center boundary. The area defined by the 150-mi extension will serve as the simulation airspace. Intersections of arrival routes and the threshold define entry points for flights originating from outside the Center airspace. Airports feeding these entry points are called external origins or airports. Remaining entry points are defined at airplane top-of-climb positions along the appropriate routes. These airports inside the threshold are referred to as internal origins or airports.

5.1.1 Data Requirements

Figure 16 illustrates inputs required by the traffic preprocessor. The following paragraphs describe these inputs in more detail. The route data base used in the model is summarized in Appendix B.

The Quick Reference Edition (QRE) of the Official Airline Guide supplies all scheduled traffic data and is available in tape format. When the date (day of the week, month, and year) and destination airport (e.g., Denver Stapleton) are specified, data (as typified in fig. 10) arranged according to scheduled arrival times are provided for use as the scheduled-traffic source for the demand model. The following are supplied: airline identifier, flight number, airplane type, origin airport, nominal departure time from origin, nominal arrival time at Denver, flight time (in minutes), and trip distance (in nautical miles).

The analysis time period is defined by beginning and ending clock times during which traffic will be processed. The corresponding demand list is constructed by the traffic preprocessor.

Specification of the active runway causes the algorithm to load nominal meter fix-to-runway (terminal area) transition times. These terminal area transition times (as well as transition distances) are shown in Table 1 and discussed further in the next section.

The mixture of TNAV equipage is an input specification to the traffic model. The specification defines percentages of the total commercial jet input traffic which are unequipped (no TNAV capability), partially equipped (with TNAV advisory systems), or fully equipped (with TNAV systems coupled to the autopilot/autothrottle for time control). Section 5.4.2 covers additional aspects of TNAV equipage. Analysis described in Section 6 assumes only fully equipped and unequipped aircraft.

Another pair of input parameters are the numbers of two types of random arrivals expressed as percentages of scheduled traffic within the analysis time period. One specifies the number of unscheduled low-performance airplanes; the other specifies the number of high-performance airplanes. Low-performance traffic is assumed to originate from an internal airport. Random high-performance airplanes can come from any of the simulation origins.

In addition to data supplied as inputs, the traffic model requires several data bases to generate the traffic demand list. These consist of airport, airplane, and airspace characteristics which are time-of-day invariant.

The lateness distribution supplies a random perturbation to an airplane's nominal (scheduled) arrival time. This modification results in tentative arrival times which are the basis for computing demand times at entry points.

Table 2 is a statistical summary of lateness distribution relative to scheduled arrival time at Stapleton. No satisfactory fit was achieved with several simple theoretical skewed probability density functions (i.e., ERLANG, GAMMA, LOG NORMAL). Therefore, a table look-up routine of delay vs. cumulative probability (reflecting the empirical data) is used. Actual discrete cumulative distribution is shown in Figure 17.

In order to compute commercial jet gross weight at an entry point, the demand model adjusts a typical landing weight by an average fuel burn over the total arrival path distance. Each airplane type has a unique landing weight distribution and average fuel burn, as shown in Table 3. Distribution is assumed to be a truncated normal with limits of $\pm$ one sigma. Standard deviation is arbitrarily specified as 5% of the mean.

The route data base (appendix B) summarizes all airspace-dependent data which the traffic model uses to assign initial characteristics to each commercial jet, commuter airplane, or random high-performance airplane at its entry point. The model identifies 70 entry points, each of which has associated one or more origin airports. The August 1980 QRE data lists 123 airports which have departures directly bound for Denver Stapleton. The route data base designates a specific entry point, meter fix, and cruise altitude for each airplane which depends on its origin and airplane type. No alternate routes to Denver, path off-loading, or random altitude assignments are assumed in the current simulation.

United Airlines designates primary routes into Denver. Secondary routes are used as a result of weather disturbances or unusual winds. For purposes of the simulation, the United Airlines system of route assignment is assumed as the assignment system used by all other major carriers on common routes. In assigning routes not served by United, most likely routes are assumed, corresponding for the most part to published jet routes and airways. Where appropriate, "direct to" segments are inserted. No secondary routing is used by the traffic model. Therefore, every origin airport is correlated to a particular entry point, although any entry point may serve several origins.

In general, initial altitude at the entry point is a function of trip distance and airplane type. Altitude assignment is also consistent with ATC regulations based on magnetic course as shown below.

IFR Cruising Altitudes in the U.S. and Canada

Flight level reference	Magnetic course	Cruising altitude
< FL 290	180-359	FL 180, 200, 220, . . .
< FL 290	360(0)-179	FL 190, 210, 230, . . .
⩾ FL 290	180-359	FL 310, 350, 390, . . .
⩾ FL 290	360(0)-179	FL 290, 330, 370, . . .

Typical cruise altitudes at "external" entry points are derived from altitudes filed for by United Airlines (1981) for its high-performance jet flights into Denver and from data supplied by the Denver Center. Non-United routes are assigned altitudes consistent with those used by United Airlines.

Altitude assignments at "internal" entry points are based on calculation of a climb to the highest attainable altitude while allowing for a practicable low-speed descent to Denver Stapleton. For airplanes departing from sufficiently close airports, assumed flight plans involve the climb phase followed by the descent segment. However, no climb segment is permitted beyond the meter fix. In other cases, maximum cruise altitude (consistent with the restrictions in the above table) can be reached before descent is begun.

United Airlines obtains clearances for its requested cruise altitudes over 99% of the time. It is assumed that the same efficiency can be applied systemwide. No randomness is therefore introduced into altitude assignment modeling.

Depending on the metering scenario in effect (sec. 4.4), the air traffic control function may have airplanes absorb some system delay by ground holding. Under internal metering conditions, only those designated as eligible in the "metering" column (fig. 10) are considered for ground delay absorption. When expanded metering is in effect, those arrivals associated with eligible airports are considered. A third designation is established for aircraft ineligible under any condition and who must absorb delay in the freeze region on approach.

Cruise transition route distances from external entry points to their associated meter fixes were taken from high altitude charts for Denver Center. Cruise transition distances of internal entry

points were computed from the top-of-climb point to the associated meter fixes. In order to avoid recomputing this point for every airplane type, B737 climb performance is assumed because it is most representative of commercial turbojets from internal airports. Noncommercial airplanes typically need less distance to climb to the same altitude as commercial jets; so the B737-derived top-of-climb point is an achievable albeit conservative one for the commuter and random high-performance airplane categories.

5.1.2 Functional Description

The function of the traffic preprocessor is to create the traffic list which the flow management simulation uses to introduce new aircraft into the simulation at appropriate times and with appropriate initial conditions (position, speed, weight, etc.).

Figure 10 shows an excerpted sample demand list. The significance of each column is also indicated. Processes by which the traffic model generates these data are described in the following sections.

Functional architecture of the traffic model is illustrated in Figure 18. Random traffic is generated, assigned flight plans, and interspersed with scheduled traffic. Based on aircraft type and origin information, entry point characteristics (entry point name, altitude, distance to meter fix, weight, speed, and time-of-arrival) are established. The demand list is then sorted by entry point time.

The airplane flight identifier consists of either (1) airline identifier and flight number (both obtained from QRE data) and aircraft type for an OAG-scheduled arrival; or (2) designation that the flight has been randomly introduced and whether it is a low-performance or high-performance generic airplane type (RLxx or RHxx, respectively).

Airline companies serving Denver Stapleton during August 1980 are listed in Table 4. For a scheduled arrival, the two-letter identifier appears both in the QRE input data and the demand list. Flight numbers and original airplane types are extracted directly from the QRE.

In order to simplify simulation, every original commercial airplane type appearing in the scheduled traffic list (OAG data) is converted to an equivalent Boeing airplane type (B727, B737, or B767), commuter airplane category, or low-performance airplane. Though certain wide-bodied turbojets (DC-10, L-1011 and Airbus A-300) have characteristics between a B767 and B747, they are classified as the former type for convenience. Equivalency assignments are denoted in Table 5. Although several of the jets in Table 5 do not currently operate at Denver, their inclusion anticipates simulation of other U.S. airports.

For purposes of simulation, commuter performance characteristics are estimated. These are described in Section 5.4.4. OAG-listed, Denver-bound airplanes classified as commuters are itemized in Table 6.

All other OAG-listed airplanes to Denver (table 7) are designated low-performance airplanes. In general, they differ from the aircraft of Table 6 by their lower thrust performance and gross weights, and by their lack of cabin pressurization equipment, thereby confining them to lower operating altitudes.

Using random traffic input specifications, the demand model introduces random traffic. These represent unscheduled arrivals and are classified as either random high-performance or random low-performance aircraft types in the same category as those of Tables 6 and 7. Identifiers designating either a random high-performance (RH) or random low-performance (RL) are assigned along with a number, picked sequentially.

In the model, assignment of TNAV capability is confined to commercial jets, reflecting the trend among major U.S. carriers of equipping their fleets. Assignment is randomly made, subject to airplane type restriction. The traffic preprocessor maintains an internal count as it assigns various levels of TNAV equipage to conform to input requirements.

Tentative arrival time is generated as follows: A random number is generated from a normalized uniform distribution and applied to the lateness distribution (table 2). The lateness term is calculated by linear interpolation.

A flight's entry point characteristics are the starting point for the profile generation function to compute the airplane's path to the meter fix. The air traffic control function uses the demand time as a basis for deciding when the airplane is to be introduced into the simulation. Its simulation entry time also may depend on the type of metering in effect and system delay.

Entry point characteristics consist of an airplane's entry point, altitude, time-of-arrival, gross weight, and speed at entry point. All of those data are generated for scheduled commercial jets and all but gross weight for commuters. Only times of arrival are supplied for low-performance aircraft.

Based on a flight's origin, the model assigns an entry point and an initial entry point altitude in accordance with the route data base (appendix B).

Only commercial jets will have an assigned landing gross weight. From the landing weight assignment, an initial gross weight at the entry point is computed by assuming an average fuel burn (table 3) over the distance from the entry point to the runway.

Commercial jet entry point speeds are assumed to be at or near long-range cruise (LRC). Speeds are assigned based on a one-sided normal (on the faster side) distribution with a narrow standard deviation of 1% of the mean. The mean is the LRC speed of the jet. This reflects the assumption that airlines plan to fly at and maintain fuel-efficient speeds. LRC is a function both of cruise altitude and gross weight.

Since no weight data for commuter or random high-performance airplane types are carried, assigned speeds depend only on cruise altitude. As stated before, speeds are not assigned to low-performance aircraft.

Elapsed time between the entry point and runway can be computed given a commercial jet or commuter's true airspeed, terminal area transition time, entry point to meter-fix distance, and a zero-wind assumption. Demand time, or time at entry point, is then determined from the tentative arrival time.

A 5-nmi separation will be assured between every pair of aircraft (excluding low-performance aircraft) crossing the same entry point at the same altitude. At a given entry point, the difference between two successive entry-point times will be combined with the trailing airplane's groundspeed to calculate its separation distance relative to the airplane ahead. If the 5-nmi criterion is not met, then the trailing airplane's groundspeed is used to calculate the time interval needed to satisfy the separation requirement. The interval will then be added to the leading airplane's entry point arrival time to establish the entry point time of the trailing airplane. This process results in the demand list of validated demand times.

Tentative departure times from origin airports are computed by adjusting tentative arrival times by the respective flight times (supplied as a QRE input). The ATC function of the simulation uses an airplane's tentative departure time as the basis for assigning an actual departure time. The latter takes into account any ATC-directed ground hold at internal and selected external airports.

5.2 ATC PROCESSING

Simulation of the air traffic control function (excluding the metering automation) in the model is accomplished in a group of subroutines referred to as the ATC module. This module also coordinates use of the arrival metering and profile generation modules described in Sections 5.3 and 5.4, and controls generation of the statistics output by the main program.

The ATC module simulates surveillance of aircraft by ATC instrumentation, determines and issues clearances to simulate the ATC function, determines any ground holding, updates the lists of active aircraft, coordinates calls to the arrival metering and profile generation functions, checks for conflicts due to ATC separation violations, and determines statistics on throughput, route use, meter-fix use, clearances, conflicts, fuel usage, and accuracy of making the assigned meter-fix time.

5.2.1 Data Requirements

ATC module inputs may be divided into two categories—those associated with "program controls" and those needed to represent ATC processes. Program control inputs include initialization of data bases, determination of the number and clock times of statistical periods, simulation start time and duration, and simulation clock step size. Other inputs relate to modeling of ATC processes such as routing, clearance generation and conflict detection. These are discussed below.

When a new aircraft enters the simulation, the ATC module assigns a route of flight. This route assignment is based on data contained in the route data base. The route data base contains, for each simulation entry point, the sequence of waypoints, the course and distance interval between waypoints, and any "published" altitude or speed restrictions. These route data are "placed" in the profile array of each new aircraft upon simulation entry.

Ground hold inputs used by the ATC module include the ground hold calculation interval, flags to establish the status of internal and expanded metering for a particular simulation, and the "delay discount" value to be used. The "delay discount" establishes the percentage of total delay that can be taken on the ground.

ATC clearance generation uses input delay threshold times, airspeed adjustment values, and available holding altitudes (maximum and minimum) and speeds. Delay threshold times are used to represent controller responses to various levels of delay. A user may establish a threshold or thresholds below which a speed reduction is applied and above which vectoring or holding will be required. This feature allows modeling of a wide range of delay absorption techniques used by various controllers and different centers.

The conflict detection routine requires as input critical separation values which determine whether a conflict has occurred. These include minimum vertical separation (which can vary with flight level) and minimum lateral separation.

5.2.2 Functional Description

To control the simulation, this module sets and increments the clock for the system. It also determines when to activate or stop statistical periods, and stops simulation after a specified time duration.

The surveillance function is accomplished by interpolating the path data computed in profile generation for the current clock time for nonholding aircraft. For aircraft in holding, the surveillance function determines the aircraft altitude in the stack. When an aircraft is beyond the meter fix, the surveillance module collects statistics on fuel use, meter-fix arrival accuracy, conflicts, and clearances.

Clearances are issued only at the time of freezing the aircraft schedule time and when exit from the holding stack is required. Delay of the newly-frozen unequipped aircraft is compared with input delay threshold in order to choose among delay absorption alternatives. If the delay is zero, the plane is allowed to proceed at its current speed. Otherwise it is given a specified speed reduction. For delays between two specified values, a vectoring clearance is given. For delays exceeding the larger of these values, a holding clearance is given. Clearances from the holding stack depend on equipage of the aircraft. Equipped planes are issued an exit hold altitude clearance only. Unequipped aircraft are controlled by ATC to depart the hold fix at the correct time as well as altitude.

When appropriate, ground holding is modeled by altering the scheduled departure time. At 10-min intervals, the traffic list is searched for eligible aircraft with departure times in the following 10 min. The system delay is added to the entry-point time and a VTA is determined for internally metered planes. For expanded metering, system delay minus a discount is used to adjust the VTA.

Updating the active aircraft list is accomplished by comparing the entry-fix time with the clock time to determine entry of an aircraft. The clock step employed during the simulation was 30 sec. When surveillance determines that an aircraft is beyond the meter fix, it is removed from the active aircraft list.

The ATC module controls coordination with the arrival metering and profile generation modules by calling arrival metering to determine any newly frozen aircraft, issuing clearances to any such planes, and then calling profile generation to determine the path required by the clearance. The list of active aircraft is scanned on every iteration to check for conflicts. The two categories

used are aircraft on the same path segment and those on converging paths. Input ATC horizontal and vertical separation criteria are used. Conflicts are counted between a specific pair of airplanes only once. Since conflicts are not resolved, they may persist for several iterations. Data are saved on the identifications of the aircraft involved, their equipage, and the time at which the conflict occurred. These data are used in deriving output statistics.

5.2.3 Output

Statistics are compiled at the end of each input statistical period. They are printed and written to a disk file along with the values of several independent variables for use in graphics postprocessing. The statistics include the number of clearances and conflicts for several categories, throughput for each performance type, fuel usage by several categories of aircraft, counts of the number of aircraft leaving the simulation, route loading, meter-fix loading, and conflict data.

5.3 EN ROUTE METERING PROCESSING

The arrival metering module determines, for each iteration, a list of newly frozen aircraft, delay data, a list of meter-fix times for use by other modules, and a list of aircraft position data for the map postprocessor. When a change has occurred, it also prints metering and freeze lists in a format similar to those appearing on plan view displays at the metering position in an ARTCC. Various intermediate results can be printed, such as the priority-ordered landing list, vertex time of arrival (VTA), and calculated landing time (CLT). The ERM functioned logic is based on the ERM functional specification published by the FAA (ref. 5).

In determining time information, the module uses present speed and distance from the next waypoint. These are furnished by the ATC module.

In determining the freeze list, a system of priorities is set up for the aircraft. These are detailed in the functional description.

A special feature of the module is the use of linked lists. These facilitate handling arrays in which removal of elements occurs in a nonuniform manner. By maintaining a system of pointers to the array elements, the module can ignore elements no longer in use and reuse those positions when needed without moving any other array elements.

5.3.1 Data Requirements

Data required by this module are lists of aircraft, airport characteristics, the clock time associated with the iteration, and path information. Also required are values of basic metering algorithm control parameters.

Aircraft lists are of three types. The most extensive is the high-performance type (commercial jets, commuters, and random high-performance airplanes). This consists of an aircraft identification, a path identification, coordinates of the aircraft position (identity of the next waypoint, distance to the next waypoint, and speed), and the ground hold time (which may be zero). The low-performance aircraft list consists of an aircraft identification, expected time at the runway, and ground hold time.

The ground hold list consists of an aircraft identification and the expected time at the runway. Airport characteristics required are the last available runway time (LART) and the aircraft arrival interval (AAI).

A data store, ROUTLIB, provides path information, as specified by the path identification.

Values of metering algorithm control parameters are set at program initialization. Parameters set include the flow control display interval (FCDI), freeze calculated landing time (FCLT), meter list display interval (MLDI), sector list drop interval (SLDI), and flow time update interval (FTUI).

5.3.2 Functional Description

The module processes the three types of aircraft lists described above, constructs a priority-ordered landing list, sequences and schedules aircraft, determines delays, constructs meter and freeze lists, and determines position data for the map postprocessor.

For each of the three lists, aircraft are subdivided into previously introduced aircraft and those which are new to the simulation in the current iteration. In each case, previously introduced aircraft are processed first.

In the case of high-performance aircraft, FTUI is checked to see if a new vertex time of arrival (VTA) is needed for unfrozen aircraft. VTA is determined by using current speed, position, and adapted data.

VTA is calculated in a similar way for ground hold aircraft.

For low-performance aircraft, the estimated time at the runway is taken as the VTA.

Unfrozen high- and low-performance aircraft are also checked for freeze eligiblility. Ground hold aircraft are frozen as they enter the simulation. The priority-ordered landing list is constructed by selecting aircraft according to priority and then sorting the sublists in increasing time (VTA) order.

Sequencing and scheduling require determination of the next available landing time (NALT), selection of the next aircraft, assignment of a calculated landing time (CLT), and determination of the delay data for each aircraft and cumulative delays in various categories. Selection of the next aircraft involves determination of the next aircraft of highest priority from the remaining unscheduled aircraft. If there is an unused landing slot (determined from NALT and AAI) preceding the CLT of this aircraft, a check is made for the use of this slot by an aircraft of lower priority. In this way, unused landing slots can be utilized when an eligible aircraft enters the simulation.

Delay of an aircraft is determined from the difference of its CLT and VTA. The corresponding meter-fix time is obtained by subtracting from the CLT the time required to fly from the meter fix to the runway.

Meter lists are obtained by sorting unfrozen aircraft by meter fix and sorting these sublists into descending meter-fix time order. The freeze list consists of all frozen aircraft (priorities 1 through 4) sorted into descending CLT order.

Six priorities are used in the arrival metering module to describe the status of aircraft. Priorities are listed in descending numerical order, which is the order of increasing importance.

(6) When an aircraft first enters the airspace, it is given a priority of 6. This designates an aircraft which is new during the present iteration. The aircraft is considered as a "new" unfrozen aircraft. Upon the next iteration, its priority is changed to 5.

(5) This priority indicates an "old" unfrozen aircraft.

(4) This priority represents a newly frozen active aircraft.

(3) This priority represents a new ground hold aircraft.

(2) Priority 2 designates a previously ground held aircraft which has entered the simulation as an active aircraft and has a VTA later than the previously assigned CLT.

(1) This is the priority for an "old" frozen aircraft.

A typical sequence of priorities is as follows:

An aircraft which enters the airspace has a priority of 6 during the first iteration, but then changes to a priority of 5 until it reaches the freeze region. Then it becomes a priority 4 in the iteration in which it becomes frozen, followed in the next iteration by priority 1.

A ground hold aircraft starts as priority 3 during its first iteration, and then becomes a priority 1.

An aircraft taking off from an airport within the freeze region is assigned a priority of 4 during its first iteration. It then becomes a 1.

To summarize, frozen aircraft have priorities 1 through 4. Other aircraft have priorities 5 or 6.

5.3.3 Output

Output from this module consists of meter lists, freeze lists, data which is passed to the ATC module, and a disk file of map position data. Printed metering lists and the freeze list are formatted as they appear to the controller at the metering position in an ARTCC. All active and ground held aircraft appear on one of these lists.

A disk file of map position data consists of entry points, waypoints, distance from the waypoint in nautical miles, and altitude in feet. A count of the aircraft using a particular entry point is

included so that successive aircraft are plotted with different symbols. This file can be transferred to a graphics computer for use with the map postprocessor and plotted with the three-dimensional plotting package.

5.4 PROFILE GENERATION PROCESSING

The profile generation module produces flightpaths of the active traffic set. These profiles are calculated when aircraft first enter the simulation and thereafter when they respond to ATC clearances. The path computation process results in airplane speeds, altitudes, gross weights, cumulative distances, courses and times of arrival at all published and performance-generated waypoints from the airplane's entry point to its designated meter fix. These paths conform to all published ATC speed and altitude restrictions along the route of flight. Zero winds and ISA temperatures at all altitudes are assumed. Moreover, for commercial turbojets, airplane performance data are used to generate computed profiles.

The ATC function monitors aircraft entry, flight progress, and exit. It generates clearances when metering is required. ATC therefore decides when to enlist the profile generation function. For each newly active airplane, path processing initially generates a control-free path from the simulation entry point to its assigned meter fix, given the airplane's initial conditions (cruise altitude, speed, simulation entry time, planned route, and in the case of a commercial jet, gross weight). These initial paths generally require no modification in the absence of metering. When clearances are issued to an active airplane, a revised path is generated which takes into account any appropriate changes in airplane state caused by complying with those clearances. The revised path is recomputed from the aircraft's present position to the meter fix. During every clock cycle, currently stored paths of all active aircraft are used by the ATC function to determine surveillance data (groundspeeds, altitudes, distances to the next published waypoint).

In the current implementation of the model, clearances are issued only at the freeze point and the hold fix when system metering is in effect. The nature of the clearance depends on the airplane's TNAV equipage and position at the time of the clearance.

5.4.1 Data Requirements

The profile generation algorithm requires weather (vertical wind and temperature profiles), performance data for commercial jets, and an active aircraft list.

According to the commercial airplane type, the algorithm accesses performance data whenever a path calculation is required. Figures 19 and 20 illustrate engine and airframe data base architectures, respectively.

The ATC function supplies path generation logic with a list of active aircraft. The list is a sequence of aircraft indices which map into the traffic demand list. The aircraft index is used to load into the path buffer the current airplane's designated route of flight; initial (entry point) speed, altitude, gross weight (for commercial jets), and distance to the meter fix; assigned meter fix altitude; airplane type; TNAV system equipage; identity of its assigned meter fix, transition fix, and hold fix; and applicable clearances. The active aircraft list is updated every clock cycle.

5.4.2 Equipage Performance Considerations

TNAV equipage assignment is assumed only for commercial jets. The level of equipage determines to a large extent how a path segment will be calculated.

Unequipped airplanes, which in the model include all those in the commuter jet and random high-performance categories, have no means of optimizing performance, either in time or fuel. They must rely on ATC to deliver them to the meter fix on time when system metering is in effect. Intervention takes the form of speed clearances or vectors.

3D flight management systems couple a lateral navigation capability to the vertical, permitting fuel savings over an entire route. A 4D (with TNAV) advisory FMS installation is able to compute a speed schedule to make good an input time at a future waypoint (such as a meter-fix time), based on a measurement of the current cruise wind. However, lacking closed-loop control on the airplane's current groundspeed, the advisory system is unable to deliver the airplane at the desired time with high precision, especially when it encounters unpredicted winds. This capability places its performance somewhere between a conventional 3D system and a fully coupled 4D system. Advisory system errors can be minimized with periodic pilot updating action. Because of pilot workload considerations, however, 4D advisory time delivery accuracies are not expected to be as good as those of fully coupled 4D systems.

Given a time target at the meter fix, the model calculates a vertical and horizontal path for the 4D-equipped airplane by specifying altitudes, speeds, and times at all intervening waypoints. In this analysis, only unequipped and closed-loop 4D-equipped (TNAV) aircraft are assumed.

5.4.3 Speed Clearance Limitations

Speed clearances are given in the form of a change in indicated airspeed. Unequipped airplanes are issued speed clearances. The ATC function assigns a speed reduction based on the required delay. The new required speed sometimes may exceed the aeroperformance limits of the airplane. In such cases, the airplane will comply with the ATC directive by flying as close to the assigned speed as possible. The profile generation function simulates selection of the final practicable speed by a series of tests. All possibilities are shown graphically in Figure 21.

If the assigned speed is slower than the airplane's low-speed capability, the airplane will descend at the low-speed limit.

An airplane assigned a speed between the low-speed and high-speed limits will fly at the commanded indicated airspeed. The actual speed to comply with an assignment faster than the high-speed limit is determined after additional considerations. In the case of a commercial jet, the high-speed boundary is determined by one of the following: high-speed initial buffet, thrust-limited true airspeed, maximum operating Mach, or maximum operating airspeed. The first two are functions of airplane gross weight. High-speed performance limitations of the business/commuter jet are represented by gross-weight-independent MMO (0.7 Mach) and VMO (300 kcas). VMO and the limiting high-altitude, high-speed constraint intersect at a "crossover altitude."

For ATC speeds exceeding high-speed limits, the airplane accelerates to its high-speed limit prior to descent. A comparison is made at the target altitude between the ATC-commanded speed and the high-speed Mach limit. If the ATC speed is smaller, the airplane will make a transition to the commanded speed prior to reaching the target altitude. If the high-speed limit is smaller, the airplane will make a constant-mach descent from cruise to target altitude.

When the cruise altitude is above and the target altitude is below the high-speed crossover, the airplane begins its descent at the high-speed Mach limit. Then, a transition will be made to a constant indicated airspeed, which is the lesser of the ATC-commanded speed or VMO.

When the cruise altitude is below the high-speed crossover, the airplane will make a constant indicated airspeed descent at VMO.

5.4.4 Descent Flight Path Assumptions

Vertical descent profiles for commercial jets are generated by a clean configuration (no spoilers) and idle thrust, or by a configuration with spoilers and idle thrust. A spoiler descent is used when altitude constraints at two successive waypoints require a descent steeper than that achievable at clean idle. Where altitude constraints require additional thrust, an intermediate level segment is installed to provide additional thrust. Profiles are computed by solving the airplane's basic point-mass, steady-state equations of motion using airplane and engine performance data.

Rather than ascribing specific performance characteristics to commuter and random high-performance aircraft, constant flightpath angle descents are assumed for this class. Descent angle is assumed as 3 deg nominally. These calculations do not require gross weight data. Speeds at waypoints are determined based on the selected speed schedule. Three miles is assumed representative of the distance required to change speed after receiving a speed clearance at the freeze point and prior to crossing the meter fix or, in the case of holding, prior to entering the stack.

No paths are constructed for low-performance airplanes. They are assigned landing times by the arrival metering function, but are assumed not to interact with other aircraft and so are not represented in the simulation.

5.4.5 Path Sectors

When an aircraft enters the simulation, a control-free path is constructed assuming the current state for its initial conditions (gross weight, altitude, and speed at its entry point). Both cruise and descent phases reflect initial speed and conform to all ATC constraints (speed and target altitude at the meter fix). The initial path is stored and used by the ATC function to generate surveillance (present position) data as a function of clock time. However, following an ATC clearance, the path from the airplane's position at the time of the clearance is recomputed. Clearances can be given at two places: the freeze point and the hold fix.

If a freeze path with no holding is required, the TNAV airplane will be issued a meter-fix time, and thus it will compute a path using the appropriate calculated speed schedule to make good that time within a specified time tolerance (± 5 sec for the TNAV airplane). ATC will give all other

airplanes a speed directive with which they will comply consistent with their speed performance limitations (sec. 5.4.4).

When system holding is operational, additional clearances are needed. A meter-fix time and stack entry altitude will be given to the TNAV airplane when holding is in effect. Such an airplane will generate a path using its current speed. All other aircraft are given a speed command and a stack entry altitude. A path is computed for this type of airplane assuming a change to the commanded speed consistent with its speed performance limitations. The TNAV airplane will also receive a stack exit altitude clearance, based on required utilization of the stack levels. As in Section 5.4.6., a path will be generated using the newly computed speed schedule to make good the assigned time at meter fix. For unequipped airplanes, a speed command will be given (identical to the holding speed) and a stack exit altitude. A path will be computed using the commanded speed assuming ATC will maneuver the airplane to depart the hold fix at the proper time as computed by ATC. The equipped airplane departs holding at the calculated exit hold time, determined by the airborne TNAV system.

Time error at meter fix will generally be greater for the unequipped airplane and less for the equipped airplane regardless of whether holding is in effect.

5.4.6 Path Buffer

The path buffer contains inputs and primary outputs of the path generation function. It contains the number of path segments, number of waypoints, path courses, distances, maximum and minimum altitude constraints at each waypoint, speeds, waypoint names, computed altitudes, segment fuels and elapsed times, gross weights, times-of-arrival, aircraft type, flight management system equipage, and names of appropriate transition, meter, and hold fixes.

6.0 AN EVALUATION OF TNAV OPERATIONS WITH METERING

With increased automation in the air traffic control system, time-based control is being increasingly utilized as a means of managing high-density traffic. Various traffic management programs containing time control features are currently under development or study. At the same time, airplane manufacturers have demonstrated the feasibility of adding a time navigation (TNAV) capability to their flight management software. TNAV is also gaining more support among airline companies, as its benefits have become more apparent. This study evaluates benefits that the TNAV-equipped airplane can confer to the ATC environment. These benefits are for five different levels of commercial jet TNAV equipage (0, 25, 50, 75, and 100%). Note that even with 100% commercial jet TNAV equipage, 28% of the arrival fleet (excluding low-performance aircraft) is still unequipped. The primary result of the study quantifies the probability that an airplane equipped with TNAV will be able to use the capability for the entire descent without conflicting with any other aircraft. This probability is a major evaluation criterion of TNAV benefits. Other criteria include time accuracy, controller workload, safety, and fleet fuel.

A number of studies and analyses (for example, ref. 3) have indicated benefits of TNAV in future operations when all users have become "equipped." Questions have been raised, however, as to the benefits to be obtained for early users of such systems when most aircraft are unequipped. This TNAV equipage study examines fuel benefits to operators in transition from unequipped to 100% equipped operations and the workload (measured in terms of metering clearances and conflicts) of the ATC system.

6.1 ASSUMPTIONS AND EVALUATION CRITERIA

The flow management evaluation model, as a fast-time, multiple airplane simulation of en route arrival operations with metering in the Denver ARTCC airspace, contains functional representations of the metering sequencer and scheduler, airspace structure, and flight profile for each arrival airplane based on performance data. The sequencing and scheduling function simulates the en route metering program currently in operation in the ATC system (ref. 5). The model is the analysis tool in which evaluations can be made of efficiencies obtainable from various flow management and metering programs and benefits derived from different airplane capabilities.

Several assumptions and simplifications were made for this study which reduce the complexity of the modeling. These assumptions are described below.

The traffic list contains airplanes that appear between 0820 and 1200 (local time). Five sampling periods for which statistics are generated are spaced at half-hour intervals, beginning at 0830 and ending at the interval starting at 1030.

Sampling period	Inclusive clock times
1	0830.0 - 0829.5
2	0900.0 - 0929.5
3	0930.0 - 1029.5
4	1000.0 - 1029.5
5	1030.0 - 1059.5

The simulation requires approximately an hour to build up a representative level of en route and arrival traffic. Therefore, periods 3, 4, and 5 are used primarily in the analyses.

Traffic sets used for each of the five TNAV equipage level runs differ only in the equipage assigned to individual commercial jets. All other entry point characteristics of each airplane remain the same between different runs. Because of this, other conditions are unchanged: meter list processing, freeze times, ATC-required delays, and meter fix and route loadings.

Meter list processing provides construction of freeze and nonfreeze lists of aircraft. Calculations of predicted runway (vertex) times (VTAs) are independent of equipage type. Because freeze times are based on VTAs, they too do not depend on equipage type. Similarly, VTAs (as well as a prioritization rule based on first come-first served and ground hold considerations) determine assignment of landing times. Therefore, VTAs, CLTs, and freeze times depend only on the traffic input and remain constant in all equipage simulation runs. Since departure traffic from Denver is not modeled, landing time slot assignments depend only on arrival demand. Each airplane's ATC delay (delay required as the consequence of assigning a later landing time than its predicted runway time) is the difference between the CLT and VTA. How each flight absorbs that delay is a function of both ATC procedures and airplane equipage. Figure 22, a summary of freeze-time ATC delays averaged for each of the five simulation periods, verifies that as airport demand increases in relation to its capacity, more ATC delay is required of any individual airplane. This figure correlates with Figure 23, which plots the number of aircraft entering the simulation (therefore occupying tentative landing times) during each sampling period. Figure 24 indicates the number of high-performance aircraft processed by the simulation. The number of entering aircraft is further differentiated among the four meter fixes in Table 8. Note that the model does not resolve imbalance in meter fix loading (number of airplanes per meter fix).

There are basic assumptions and simplifications made in modeling the ATC function. Clearances are issued only at the freeze point and the hold fix. Aircraft responses to clearances issued at any time interval are assumed to be instantaneous; they are taken at the time they are issued. Types of clearances were discussed in section 5.2. Speed and vector clearances issued to the unequipped airplane are the following:

(1) An average speed reduction clearance over the range of route distances to the meter fix, and

(2) A vector given the unequipped airplane near the meter fix to absorb any remaining delay after taking into account an average delay absorbed due to the speed reduction alone.

A speed reduction of 10 kn is assumed in the unequipped airplane's indicated airspeed for cruise and for descent. Speed increases are usually not used with current metering procedures. All delay-absorbing vectors by unequipped aircraft are assumed to be undertaken near the meter fix rather than in the descent or at high altitude, consistent with observed operational practices of "meter-fix controllers" at Denver and Ft. Worth centers. Vectoring (path stretching) is represented by increasing the effective length of the segment in which vectoring applies. For the unequipped airplane, one consequence of having a single clearance point is an increase in meter-fix time-of-arrival inaccuracy, though not inconsistent in size with those experienced at Denver and Ft. Worth.

As holding procedures for equipped and unequipped aircraft are expected to be identical, they should have no impact on equipage. Thus, the required delay threshold for ATC to begin assigning holding has been set somewhat higher (15 min) in the simulation than is usually employed at Denver.

The equipped airplane requires only one clearance, the meter-fix time assignment for nonholding operations. If more delay is needed than that provided by a slow-speed descent, the equipped airplane computes its own vector distance. The model applies the vector immediately after the airplane has reached its descent speed at cruise altitude and after the freeze time. Therefore, the equipped airplane's path stretching takes place at high, fuel-efficient altitudes. Path stretching clearance is assumed to be negotiated at the same time as the basic speed/time clearance. No additional ATC clearance is counted for path stretching. As in the unequipped airplane case, path stretching is allowed for all delay required beyond that absorbed by speed control and is represented by an increase in path length to be flown. Effect of path stretching on conflicts was evaluated in postsimulation. All conflicts artificially "created" by vectoring logic were not counted by the simulation.

The above discussion demonstrates that the same clearance logic is used regardless of the equipage level of the traffic. In actual operation, ATC may develop different control strategies to accommodate TNAV aircraft in a time-based metering environment as the fleet becomes increasingly equipped. Traffic conflicts are detected but not resolved. Conflict resolution logic requires generation of clearances when conflicts occur. The scope of TNAV benefits analysis is restricted to examining the probability that a TNAV-equipped airplane can arrive conflict-free. All conflicts between any pair of aircraft are counted only once since no assumptions can be made about their subsequent interactions in the absence of a conflict resolution logic. Only Denver arrival traffic is modeled, so conflicts with departures or overflights are not considered.

Because the study assumed no winds and temperature variations, and neglects avionics and guidance inaccuracies, airplane flight paths computed by the profile generation function are assumed to be the actual flown profiles. A result of these assumptions is that meter-fix time accuracies, which can be achieved by the equipped airplane, depend solely on the ability to calculate the required speed schedule. If the airplane can absorb its delay within the available time margin (between the slow and fast-speed descent times), the speed-search iteration technique converges within 5 sec of the required meter-fix time. If more delay is required beyond that available from a slow-speed descent, meter-fix time inaccuracy will be zero since the elapsed descent time and, therefore, remaining delay are known precisely.

6.2 WORKLOAD EVALUATION

The presence of a significant percentage of TNAV-equipped aircraft in the National Airspace System is expected to reduce controller workload. The flow management simulation provides evidence relative to this expectation by determining statistics on the number of clearances issued by the ATC function and on the number of conflicts (aircraft separation violations) detected.

Clearance statistics are shown in Figure 25. The number of clearances is normalized to the average number of active aircraft in the simulation during the statistical period. The figure shows that workload increases as the number of aircraft present in the simulation increases. The upper two curves involve approximately equal average numbers of active aircraft but different number of aircraft passing the meter fix and leaving the simulation. The increased workload is associated with more vectoring (for delay absorption) when demand and competition for runway slots are higher.

An expected trend in the figure is a reduced workload on the controller as the level of TNAV equipage increases. This is due to the TNAV aircraft's ability to generate its own descent speed and path stretching maneuvers.

Conflict statistics are shown in Figure 26. The number of conflicts is normalized to the average number of active aircraft in the simulation during the statistical period. The conflict rate depends on the number of aircraft using each meter fix, as is seen by comparing the curves for simulation periods 4 and 5.

For both periods, the conflict rate is least for 0 and 100% TNAV equipages. Under both of these cases, performance of the fleet of aircraft is more uniform, reducing the probability of conflicts.

The higher conflict rate observed with mixed fleet cases is due in part to two types of conflicts. When all aircraft are experiencing some delay, the different ways of absorbing delay for equipped and unequipped aircraft create conflicts. TNAV aircraft first execute a vector at cruise altitude and then descend at their slow speed limit. Unequipped aircraft requiring 2 to 15 min of delay are given a 10-kn speed reduction for cruise and descent, and then execute a vector (as required) just prior to passing the meter fix. This leads to conflicts between two aircraft of different equipages scheduled in succession over the same meter fix.

Furthermore, ATC scheduling based on the En Route Metering algorithm and the simulated control of unequipped aircraft is such that they are typically 65 to 85 sec late (see sec. 6.5.3). This leads to a higher probability of a conflict with a TNAV aircraft scheduled to follow an unequipped aircraft over the meter fix with a planned 1-min (minimum) separation.

Since the conflicts discussed above would be resolved by a controller, an attempt was made to estimate the additional workload involved. In Figure 27, clearance and conflict statistics for periods 3, 4, and 5 have been combined. In addition, the sum of the number of clearances plus two times the number of conflicts is shown as an estimate of total controller workload. The expected downward trend as the percentage of equipage rises is still present, although the trend apparently starts at a higher equipage level.

6.3 PROBABILITY OF SUCCESSFUL TNAV CLEARANCE

The probability that a TNAV-equipped airplane will be able to complete a planned TNAV descent without interruption depends on the likelihood of conflicts developing with other nearby aircraft. The measure of "success" may be defined differently depending on the equipage level of the arrival fleet. One measure is the number of conflicts with other aircraft, assuming zero conflicts defines a successful TNAV arrival. Another may be the ability to make good a meter-fix time assignment (including a reassignment) when conflict-resolving clearances are involved. The emphasis of the latter is on the benefits of the TNAV system's functional capability to compute an appropriate route-time profile to make good any achievable meter-fix time, while the concern of the former is the immediate benefits of a TNAV system in a low-equipage-level environment with minimum impact on arrival traffic as a whole. The low-equipage-level case is of particular interest to the operator considering the benefits of TNAV capability in the early stages of systemwide implementation.

The conflict-free probability can be obtained from results of an analysis of ATC arrival operations with no conflict resolution. With a simple assumption made about resolving a certain kind of conflict involving equipped aircraft, an argument can be made for improving the success probability which is also presented below. The conflict resolution assumption involves slowing down the trailing unequipped airplane to maintain spacing relative to the leading TNAV-equipped airplane.

In this analysis, a "failure" is defined as an equipped arrival involved in at least one conflict after receiving a frozen meter-fix time assignment. An equipped aircraft does not invoke TNAV until it is frozen by the metering algorithm. Therefore, the failure criterion is applied only when the airplane is frozen. Success is the difference between 100% and the failure probability.

A summary of conflict data is presented in Table 9. Note that most conflicts occur in the freeze region (item 2) but that the proportion of freeze-region conflicts to total conflicts decreases with increasing equipage. The former observation is consistent with an increased likelihood of conflicts in denser, route-converging airspace. The latter is a benefit of wider TNAV system implementation, as the results below demonstrate. The number of frozen TNAV aircraft involved in conflicts are summarized in the table (items 3, 4, and 5). In general, there are more conflicts with the TNAV airplane in the leading than in the trailing position, a result explained by the different speed strategies employed by the equipped and the unequipped airplane. That is, the TNAV airplane slows to its slow-speed limit to absorb excess ATC delay prior to vectoring while the unequipped airplane is directed to decrease its airspeed by a fixed amount, 10 kn (with vectoring at BOD). This increases the likelihood that the generally faster unequipped airplane will close in on the equipped airplane. In item 3, four of four, five of six, three of four, and one of one conflicts are of this type for each of the equipage-level cases, respectively.

The total number of equipped arrivals (item 7), the number of equipped arrivals involved in conflicts (item 8), and the number of equipped arrivals involved in all but leading-position conflicts (item 9) are also listed in Table 9. Item 8 reflects the general tendency that most conflicts are generated when the traffic mixture is more evenly distributed between equipped and unequipped aircraft. The TNAV arrival failure rates involving all conflicts and all but leading-position conflicts are shown in item 10 and 11. Note that commercial jets (and therefore

all the TNAV-equipped aircraft in the 100% equipage-level case) comprise 72% of the total arrival traffic (except low-performance aircraft) in periods 3 through 5.

Success rates with varying equipage levels are plotted in Figure 28. Results of the analysis show that even at very low equipage levels, the equipped aircraft receives a "successful" TNAV clearance a significant percentage of the time (about 75% by extrapolation). Success probability steadily increases with increasing equipage to over 90% for full commercial jet equipage. Even if the pessimistic assumption is made that ATC will not allow a TNAV clearance when either airplane is expected to conflict, success probabilities still show a range between 35% (25% equipage) and 86% (100% equipage). This first-order conflict resolution postprocessing ignores second-order effects which may emerge as a result of slowing down trailing airplanes.

While these results apply specifically to traffic inputs used in simulation runs, they corroborate the proposition that sizable benefits accrue to initial users of TNAV systems. They also indicate a trend in which the probability increases of completing a TNAV arrival successfully (in the limited sense defined above) as more of the fleet becomes equipped. Since it seems likely that ATC will modify its current clearance methods with time to take advantage of TNAV airplane capabilities, probabilities indicated by the upper curve in Figure 28 should be achievable with operational experience.

6.4 ANALYSIS OF FUEL USAGE

This fuel usage analysis is not intended to be a cost-benefit study. The purpose of this section is to analyze trends, based on comparative fuel data, which emerge as the fleet evolves from zero to full TNAV equipage. Although these trends supplement data from previous studies of 100% equipage, this section should not be viewed as presenting a detailed evaluation of specific fuel savings. Such a cost-benefit study may be performed at a later date but would require a much larger sample size to provide an adequate statistical base.

The simulation determines fuel used by commercial aircraft (equated to a 737, 727, or 767) during cruise, acceleration/deceleration, and descent from entry point to meter fix. This data was utilized to analyze fuel consumption as a function of the percentage of TNAV equipage of the arrival fleet to quantify TNAV equipage fuel benefits.

The analysis is based on data from airplanes which exited the simulation (crossed the meter fix) during periods three, four, and five. Periods one and two were not considered since period three was the first in which an airplane reached the meter fix.

6.4.1 Fuel Burn for the Commercial Fleet

Figure 29 illustrates average fuel values for statistical periods three, four, and five combined. These averages were obtained by weighting each period's average fuel by the number of arrivals during that period. Figure 29 demonstrates the expected trend of a fuel savings of 231 lb per arrival at 100% equipage, averaged over all 36 arrivals, when compared to the average fuel burn of the same aircraft at 0% equipage.

Table 10 summarizes the mix of equipped and unequipped airplane types for each level of equipage, and shows that a total of 36 commercial airplanes were processed during periods three, four, and five. Most of the airplanes were processed during the last period (period five) when delay was highest. Table 10 indicates an imbalance of equipage assignment, especially for the 25% equipage case. The 767 and 727 aircraft fuel burn per nautical mile is 40% to 50% higher than the 737 fuel burn. The frequency of high fuel consumption aircraft in the sample, compared to the 737 frequency, is about 15% to 20% too high. The net result would be an apparent increase in fuel burn for the equipped fleet of about 10%. This phenomenon is reflected in Figure 30 which shows the equipped, unequipped, and combined commercial jet average fuel.

6.4.2 Fuel burn for the 727 Fleet

A more detailed analysis of fuel burn for equipped vs. unequipped aircraft was performed for a single airplane type. Such an analysis also took into consideration differences in freeze distance and total elapsed time in the freeze region. The 727 was selected as it was the largest in frequency and had approximately the correct mix of 4D and non-4D aircraft. Solid lines in Figure 31 depict the composition of the fleet used in the simulation, as previously tabulated in table 10. Dashed lines indicate an ideal (equal) assignment of equipage among the airplane types. The 767 category is shown to contain a disproportionate number of equipped airplanes, while the 737 category contains a disproportionate number of unequipped airplanes, especially at the 25% and 50% equipage levels. The 727 category, however, is more closely aligned with the ideal distribution of equipage assignments. Variation in actual and ideal equipage assignments is due to random assignment of equipage by the model's traffic preprocessor, combined with a limited number (36) of samples.

In addition to focusing on one airplane type, the flight region for computing fuel was here narrowed to the freeze region (from freeze point to meter fix), since only after receiving freeze clearance will any differences between equipped and unequipped aircraft appear.

Figure 32 indicates average freeze fuel for 727s as the percentage of equipage increases. At 100% equipage, 727 TNAV fuel savings average 291 lb per 727, as compared to 231 lb averaged over all commercial arrivals as previously shown in Figure 29. Figure 32 also shows that the equipped 727 uses less fuel in the freeze region than does the unequipped 727 at all intermediate levels of equipage.

Figure 33 shows 727 average freeze fuel divided by the average delay for the equipped or unequipped case. Normalization of the freeze fuel by delay does not significantly change average 727 freeze fuel trends. This indicates that delay is better distributed among equipped and unequipped 727s than it is for the arrival fleet mix as a whole, due probably to the fact that there are more 727s than any other airplane type in the simulation, which allows a more realistic random selection of equipage.

6.4.3 Summary of Fuel Results

Several characteristics of equipped and unequipped airplane fuel usage have emerged from this analysis. As discussed in the previous section, fuel comparisons between equipped and unequipped airplanes will be most meaningful when comparisons are made with fuel used in the

freeze region. This places most commercial aircraft on a more equal route distance basis, except for a few internally metered arrivals. Further, fuel burn is sensitive to delay and airplane type. Correct interpretation of simulation results requires careful consideration of these two parameters and their distribution among equipped and unequipped arrivals, especially when the sample size is limited.

6.5 METER-FIX TIME ACCURACIES

An important characteristic of a TNAV-equipped airplane is its ability to achieve an ATC-assigned time at a meter fix in an ERM environment, with a high level of accuracy and without guidance from ATC. An unequipped airplane must rely on ATC for speed commands or vectoring to meet its assigned meter-fix time. Lack of airplane performance, atmosphere, and delay absorption related data limits the controller's meter-fix delivery accuracy objective to about ± 1 min (ref. 4).

This section quantifies and compares meter-fix arrival time accuracy achieved by equipped and unequipped arrivals in the flow management simulation, and analyzes the effect of TNAV equipage levels.

6.5.1 Commuter Time Accuracy

Commuter category of airplanes are all assumed to be unequipped. The evaluation model's 30-min statistical summaries indicate that the mean commuter time error at the meter fix is -9.3 sec (a minus sign indicates a late arrival) with a 25.9-sec one-sigma variation.

6.5.2 Equipped and Unequipped Commercial Jets

Figure 34 depicts the equipped arrival's meter-fix time accuracy based on data for periods three, four, and five combined. The time accuracy mean varies from -.2 to -.8 sec as equipage varies, although this does not appear to be a strong correlation with equipage. The one-sigma level of variation is from 1.3 to 2.8 sec, appearing to increase as level of equipage increases. This increase in one-sigma values at low equipage levels is probably due to the limited sample size, particularly at lower equipage levels.

Figures 35 and 36 show unequipped and combined (averaged over entire commercial fleet of equipped and unequipped aircraft) meter-fix time accuracies also based on data for periods three, four, and five combined. Unequipped mean arrival accuracy varies from -65 sec at 0% equipage to -85 sec at 75% equipage. The apparent correlation to equipage level is probably due only to the limited sample size, particularly at higher equipage levels. The one-sigma level of variation of approximately 30 sec appears to be independent of equipage. The combined mean time accuracy reflects both equipped and unequipped accuracies. The combined mean error decreases linearly from -65 sec at 0% equipage to -.5 sec at 100% equipage. Similarly, the combined one-sigma value decreases from 30 sec to 2.8 sec as the fleet becomes fully equipped.

6.5.3 Summary of Results

It is important to note that meter-fix time accuracies computed by flow management simulation account only for errors in computing a speed schedule to achieve the ATC-assigned meter-fix time. If this speed schedule were perfectly followed, resulting time errors would be as presented in this section. No attempt was made to model factors such as guidance and control and wind prediction errors. For this reason, time accuracy results presented in this section are predictable, based on the flow management logic for equipped and unequipped airplanes.

For equipped airplanes, the descent speed generation logic determines a speed that satisfies the time constraint within a tolerance of ± 5 sec. The resulting 2.8-sec one-sigma value shown in Figure 34 is in keeping with this logic.

For unequipped airplanes, ATC speed assignment is a function of the delay to be absorbed. For delay less than 2 min, a 10-kn (kcas) speed reduction is issued at the freeze point with a constant CAS descent at that speed assumed to the meter fix. For delay greater than 2 min, the same speed reduction plus lateral vectoring is issued to absorb delay. There is no modeling of vector errors for either the equipped or unequipped airplane. The coarse increment of speed control for the unequipped airplane will obviously result in arrival time errors, and is evidenced by the 30-sec one-sigma variation in time accuracy shown in Figure 35. In addition, another time error is introduced by the original calculation of aircraft delay. The en route metering logic computes the undelayed (free) meter-fix time based on groundspeed at the entry point remaining constant to the meter fix. The unequipped arrival's actual descent speed is at a constant calibrated airspeed which results in a steady decrease in true airspeed and thus groundspeed during descent. This explains the fact that unequipped airplane time errors display a significantly negative bias (arrival is always later than the ATC-assigned time).

In placing commuter time accuracy in perspective, it should be noted that commuter cruise altitudes are much lower than most of the commercial arrivals, resulting in lower time errors due to reduced flight time in descent.

In summary, meter-fix times reflected in the simulation are representative of those expected for equipped and for unequipped users; however, approximations used in modeling delay-absorption strategies do not accurately depict all the factors contributing to real-world meter-fix delivery error.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The TNAV equipage study reported in this document provides an initial assessment of the ATC system transition from initial controller-intensive methods of time-based control (as developed at the Denver and Ft. Worth centers with the En Route Metering Program) into an envisioned distributed system in which the ground automation element provides aircraft sequencing, scheduling, and time-at-waypoint objectives and airborne TNAV flight management systems provide efficient, accurate trajectories to achieve ground objectives. Substantial benefits of such a system have been indicated in past studies; for example, the Local Flow Management/Profile Descent Avionics Research: System Requirements and Benefits Analysis, NASA CR-145341, May 1978. A critical question has been raised in reviewing such studies: "What problems will be encountered while make a transition into such a system?" This study addresses that question.

Utilizing the fast-time, multiple-airplane simulation Flow Management Evaluation Model, the TNAV equipage study indicates impact in terms of user efficiency and ATC workload of the introduction of airborne-based time-at-waypoint control capabilities into En Route Metering system operation. Basic conclusions derived from the TNAV equipage study are: (1) confirmation of previous fuel savings estimates for equipped users, (2) a decrease in conflicts between 25% and full equipage, (3) a decrease in metering clearances with increasing equipage, and (4) demonstration of a significant probability that TNAV clearances can be obtained (given typical traffic densities) even at low equipage levels. Thus, a significant probability can be applied to the expected fuel savings of initial users of the capability.

This simulation study represents an initial look at the problem of introduction of TNAV operation into the future ATC environment. Results are promising, but further work is needed in terms of real-time simulation studies, flight tests, and operational demonstrations to prove the "operability" of time navigation in both the near-term and the long-term ATC environment.

1. National Airspace System Plan, U.S.D.O.T., F.A.A., April 1985. (no number)

2. Minimum Operational Performance Standards for Airborne Area Navigation Equipment Using VOR/DME Reference Facility Sensor Inputs, RTCA D0-180, Sept. 1982.

3. Local Flow Management/Profile Descent Avionics Research: System Requirements and Benefits Analysis, J.T. Burghart and E.A. Delanty, Boeing Commercial Airplane Company, NASA CR-145341, May 1978.

4. Local Flow Traffic Management - En Route Arrival Metering, DOT, FAA Order 7110.87, May 8, 1981.

5. Computer Program Functional Specification for En Route Metering, Revision 2, Systems Research and Development Service, Computer Sciences Corporation, DOT-FA76WA-3815, March 1982.

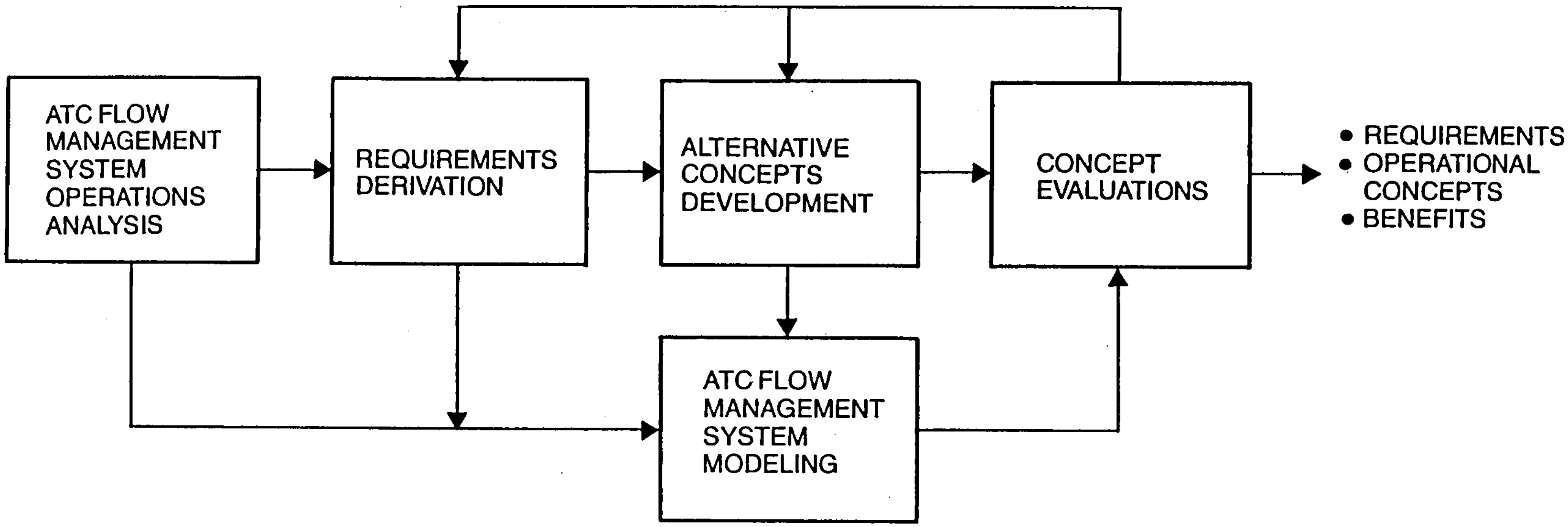


Figure 1 - Flow Management Analysis Approach

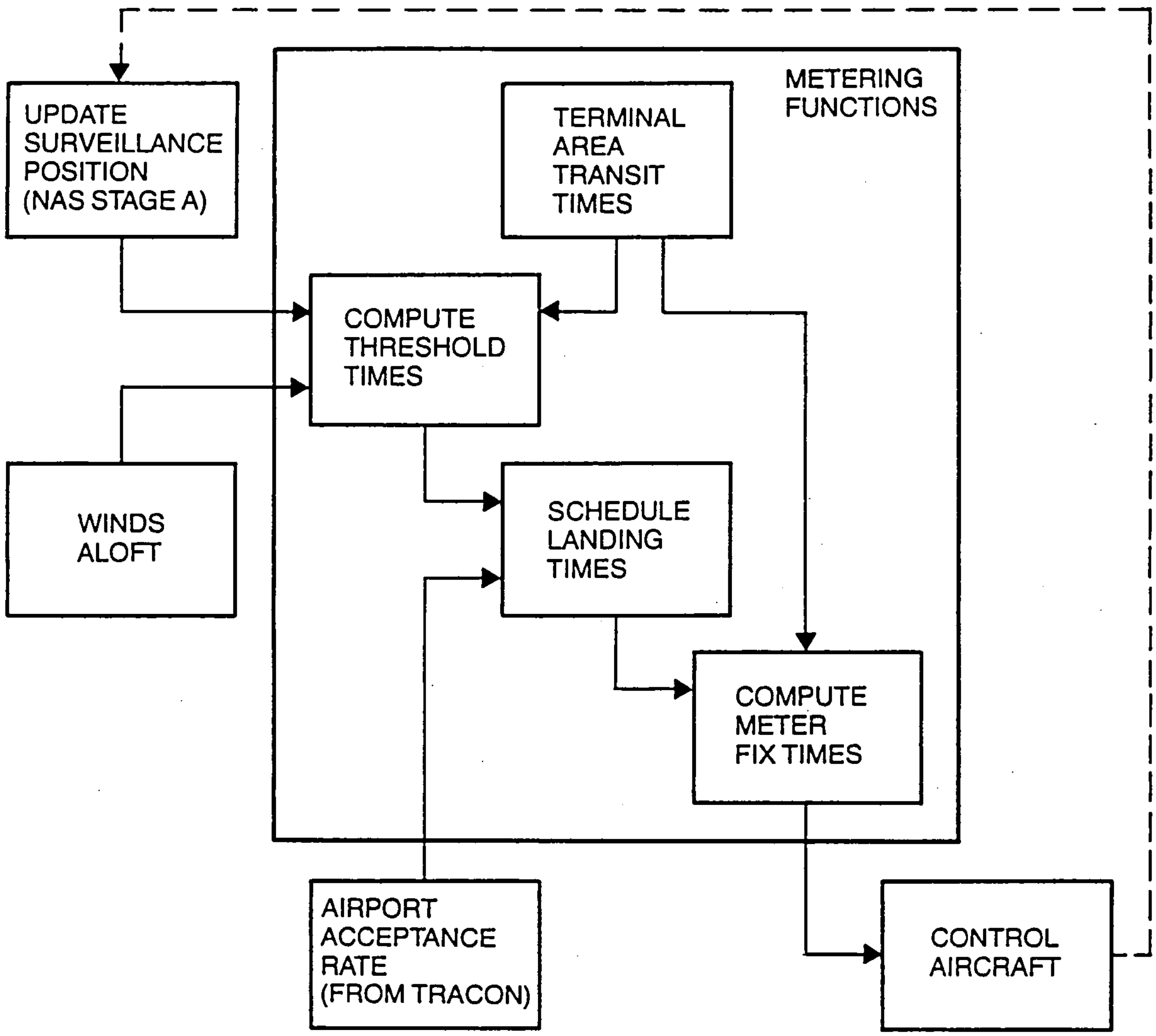


Figure 2 - Enroute Metering Functional Diagram

DEN-ARRIVAL RWY 26 **AAR 40 DELAY 2003 010**

	AID/CID		MFT	OFN	OFT	VTA	TCLT
KEANN	UAT01	324	2012	LBF	1946	2021	2022
	UA633	672	2006	LBF	1940	2016	2017
	CO221	289	1952	LBF	1938	2004	2014
IOC	BN371	603	2021	HGO	2012	2031	2061
	NW10	575	2015	HGO	2006	2025	2025
	FA245	516	1956	HGO	1949	2006	2016
DRAKO	WA46	379	2019	CHE	2000	2027	2028
	DL 327	419	2016	CHE	1958	2025	2026
	AA601	237	2014	CHE	1956	2023	2023
BYSON	TW544	557	2008	GJT	1949	2020	2020
	DL1123	353	2005	GJT	1946	2017	2019

NONFREEZE LIST

AID/CID		MFN	MFT	OFN	OFT	VTA	ACLT
FL23	614	IOC	1949	HGO	1940	1958	2000
TI939	333	DRAKO	1948	CHE	1936	1958	1959
CO404	153	DRAKO	1947	CHE	1935	1955	1957
FL136	351	BYSON	1943	GVC	1932	1955	1956
MX916	276	BYSON	1942	ALS	1926	1953	1954
BN226	457	IOC	1942	HGO	1934	1951	1953
TI270	133	NO FIX					1951

FREEZE LIST

Figure 3 - Typical Meter Fix Display

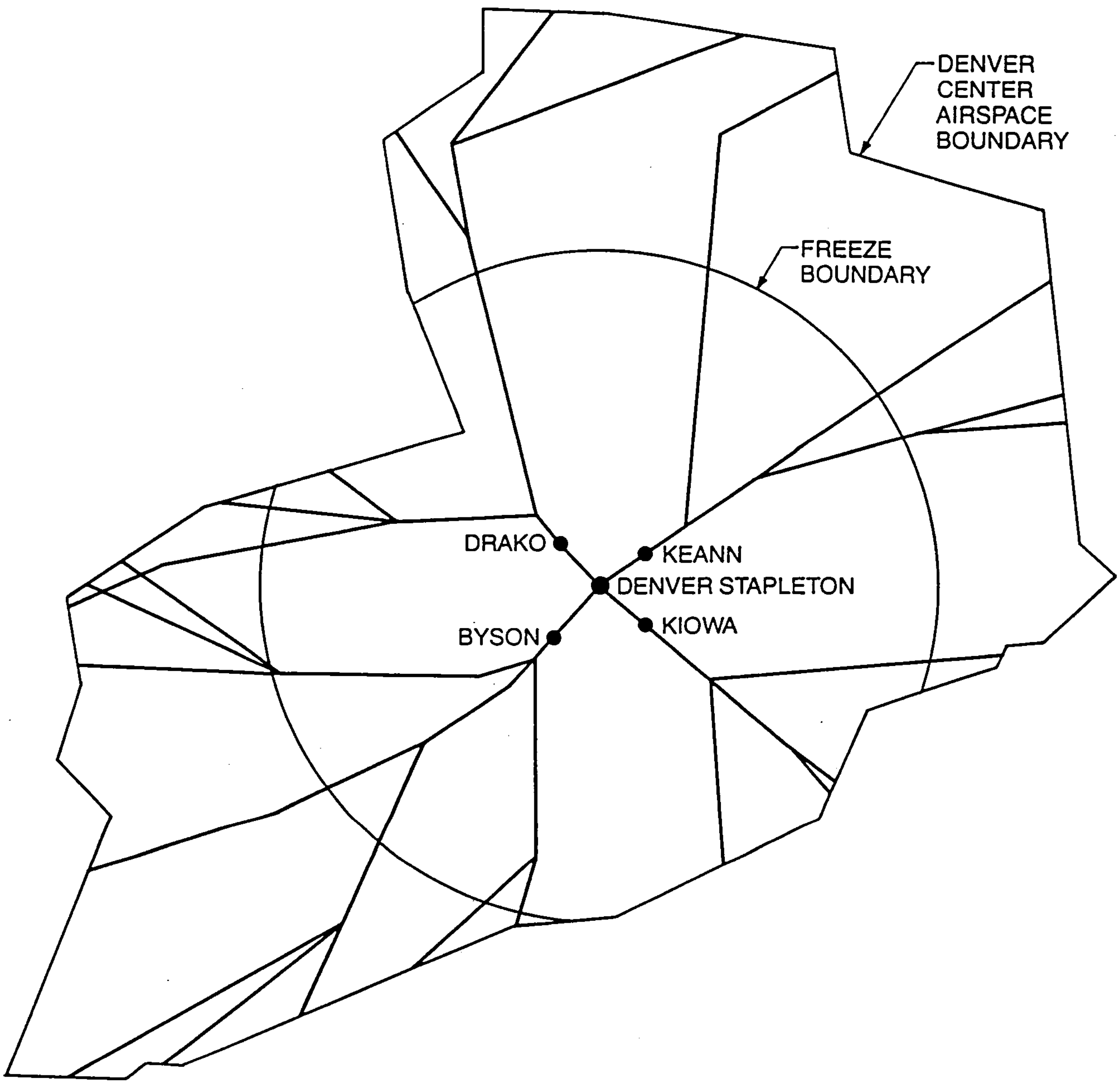


Figure 4 - Organization of High Altitude Approach Paths to Denver Stapleton

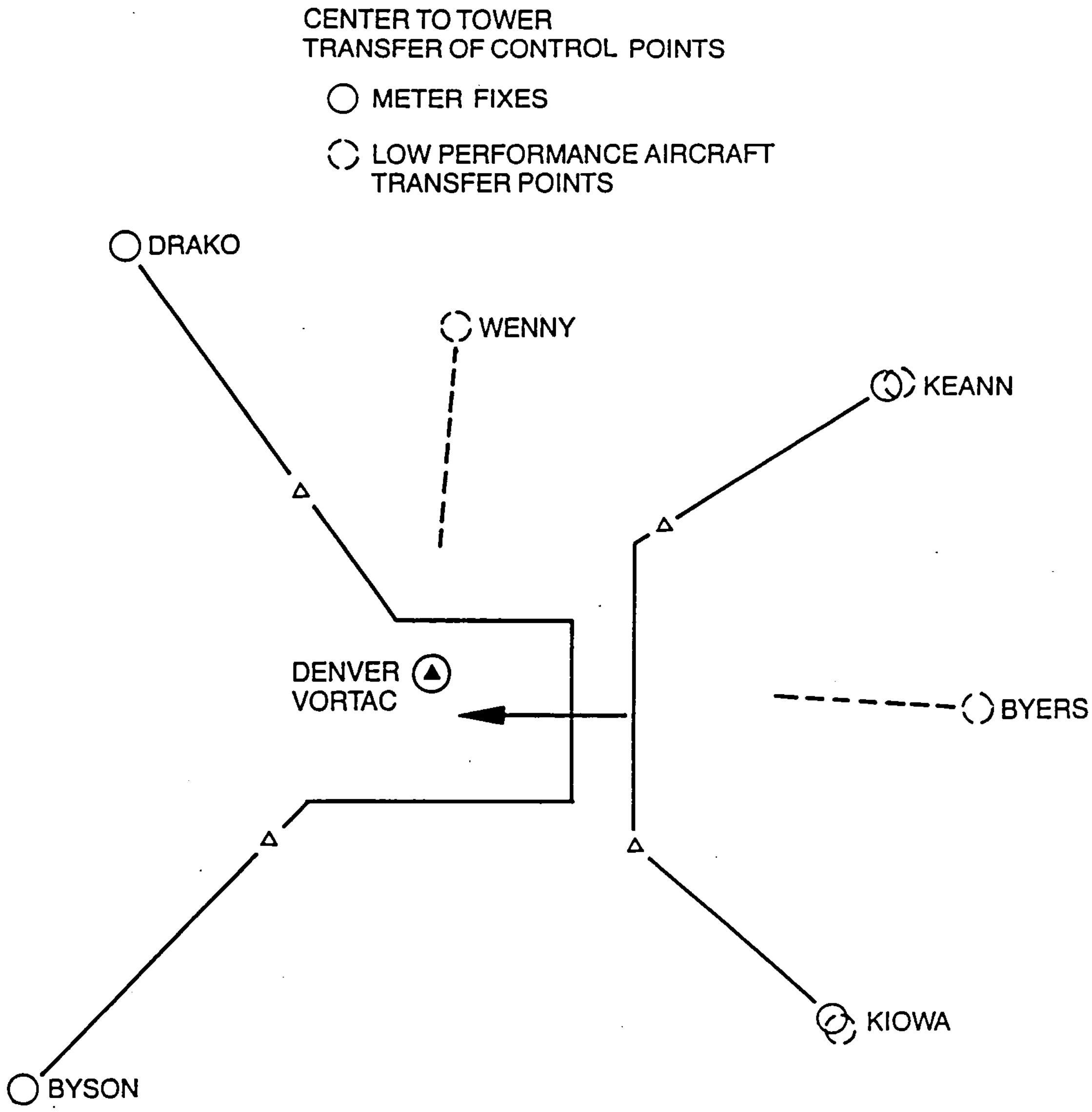
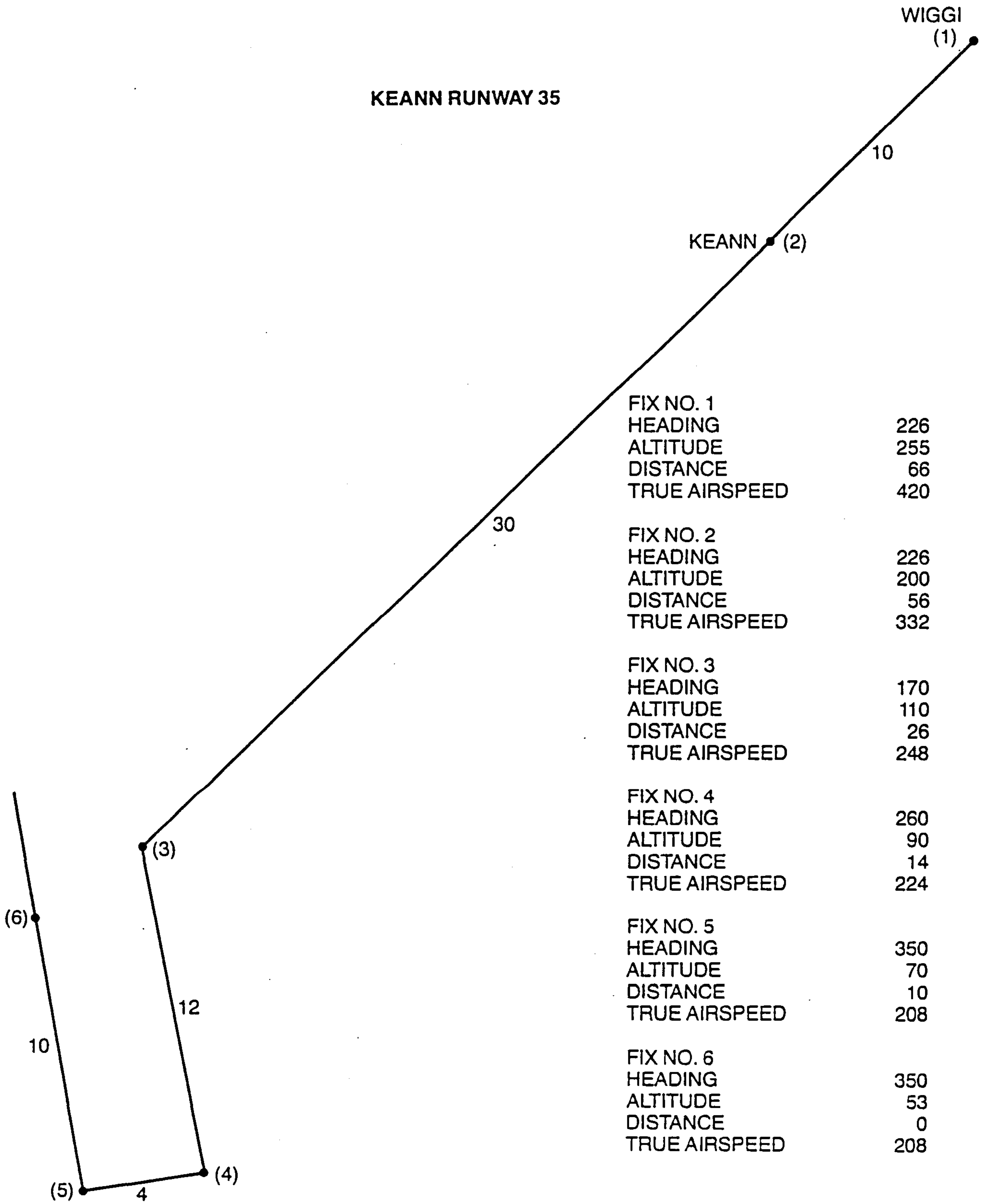


Figure 5 - Denver Runway 26 Profile Descents and Nominal Vector to Final Approach Path

KEANN RUNWAY 35



FIX NO. 1	
HEADING	226
ALTITUDE	255
DISTANCE	66
TRUE AIRSPEED	420
FIX NO. 2	
HEADING	226
ALTITUDE	200
DISTANCE	56
TRUE AIRSPEED	332
FIX NO. 3	
HEADING	170
ALTITUDE	110
DISTANCE	26
TRUE AIRSPEED	248
FIX NO. 4	
HEADING	260
ALTITUDE	90
DISTANCE	14
TRUE AIRSPEED	224
FIX NO. 5	
HEADING	350
ALTITUDE	70
DISTANCE	10
TRUE AIRSPEED	208
FIX NO. 6	
HEADING	350
ALTITUDE	53
DISTANCE	0
TRUE AIRSPEED	208

Figure 6 - Typical Runway Adaptation at Denver

NO DELAY

3 MIN AVERAGE PER AIRCRAFT: **ACTIVE METERING**

IF AIRCRAFT ORIGINATES WITHIN ZDV ISSUE GROUND HOLD: **INTERNAL METERING**

FLIGHT PROCESSING BEGINS 30 MIN PRIOR TO ENTERING ZDV; METERING FIX TIME FROZEN 28 MIN FROM DEN

HOLDING POSSIBLE AT ANY EN ROUTE WAYPOINT
PRIMARY HOLD FIXES AT RAMAH, SMITTY, BENAM, SHREW

30 MIN AVERAGE PER AIRCRAFT AND ORIGINATES NONSTOP WITHIN 75 MIN OF DEN IN ZLC, ZAB, ZMP: **EXPANDED METERING**

30 MIN AVERAGE PER AIRCRAFT AND NUMBER OF AIRCRAFT HOLDING > AAR: **QUOTA FLOW**

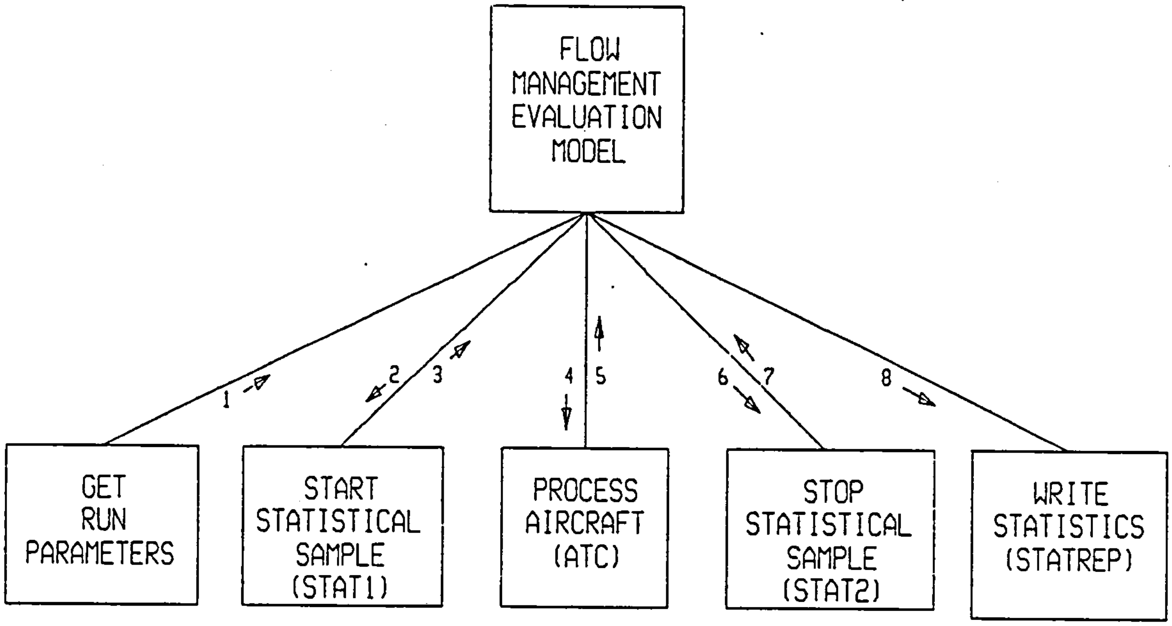
NO DELAY CREDIT FOR DENVER METERING UNLESS EXPANDED METERING APPLIES

AIRCRAFT RESTRICTED FROM ENTERING ZDV AIRSPACE

45 MIN AVERAGE PER AIRCRAFT: RECOMMEND LANDING AT ALTERNATE ZDV AIRPORT TO TAKE DELAY ON GROUND.

INCREASING DELAY

Figure 7 - Denver Center Metering Programs



1 EXPERIMENT PARAMETERS
WEATHER DATA
GEOMETRY FILE
PERFORMANCE INFO

2 STATISTICS
NUMBER OF PLANES OVER
ENTRY POINT
EXITING A/C DATA

3 STATISTICS

4 TIMES FOR ATC
METERING FLAGS
TRAFFIC INPUT FILE
NUMBERS
ARRAY PARAMETERS
AIRPORT DATA
ARRIVAL METERING DATA
ATC PARAMETERS

5 SYSTEM DELAY
A/C DELAY
FREEZE FLAG
ARRIVAL METERING
METER FIX TIME
NUMBERS OF CURRENT A/C
CLEARANCE STATISTICS
CONFLICT STATISTICS
CONFLICT DATA
EXITING A/C DATA

6 STATISTICAL PERIOD DATA
A/C ACCEPTANCE INTERVAL
EXITING A/C DATA
STATISTICS

7 STATISTICS

8 STATISTICS
STATISTICAL PERIOD DATA
CONFLICT DATA
INDEPENDENT VARIABLES

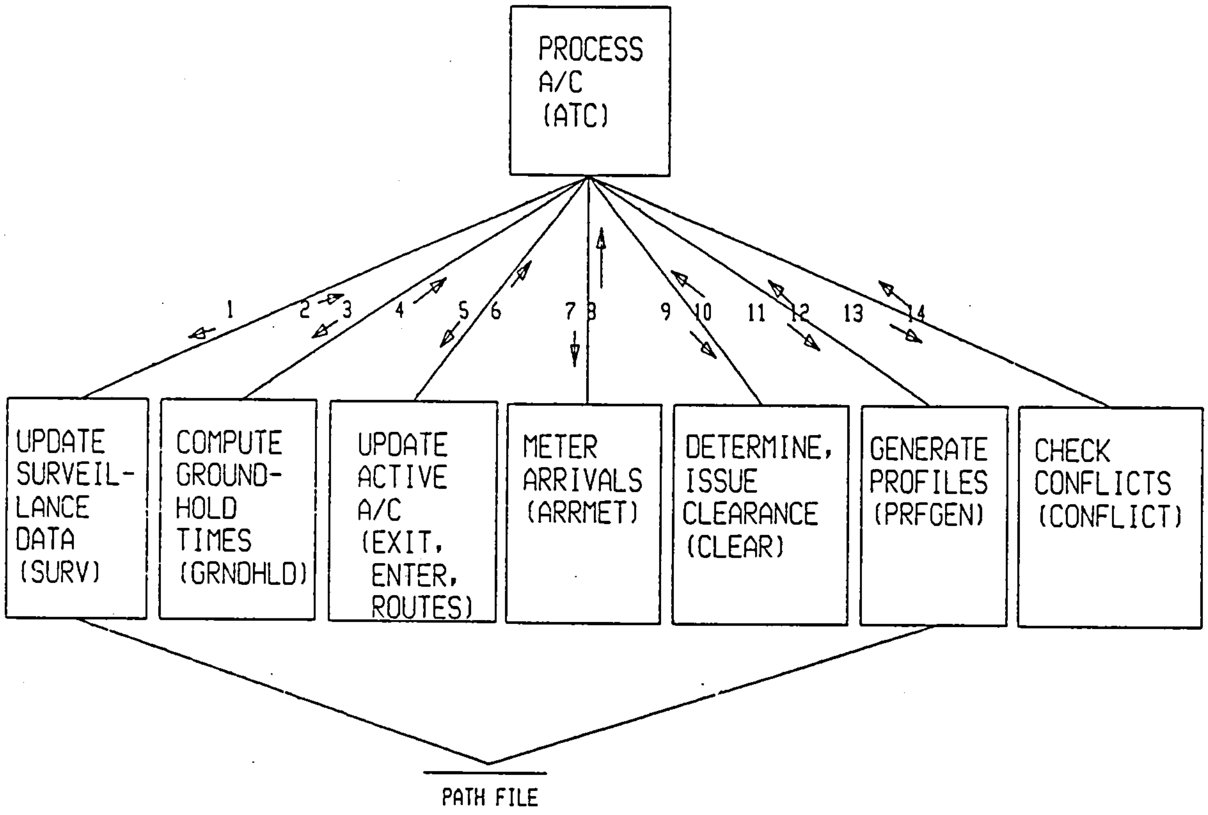
Figure 8 - Top Level Structure Chart

	OAG SCHEDULED OR RANDOMLY ASSIGNED	MAX GROSS WEIGHT	JET OR NONJET	PRESSURIZED OR UNPRESSURIZED	TYPE OF VERTICAL PATH DEFINITION	DETERMINATION OF FUEL CONSUMPTION	ELIGIBLE FOR TNAV EQUIPAGE	CONSIDERED FOR CONFLICT CHECKING	PLACED IN THE ACTIVE AIRCRAFT LIST FOR SIMULATION UPDATE	LANDING TIME ASSIGNED BY ATC METERING SCHEDULER OR RANDOMLY BY TRAFFIC PREPROCESSOR
COMMERCIAL JETS (EQUIVALENCED TO 727,737, or 767 BASED ON GROSS WEIGHT)	OAG	> 90K lb	JET	PRESS	CLEAN IDLE	YES	TNAV ELIGIBLE	YES	YES	ATC METERING
COMMUTERS	OAG	< 90K	EITHER	PRESS	CONSTANT FLIGHT PATH ANGLE ⩾3°	NO	TNAV INELIGIBLE	YES	YES	ATC METERING
RANDOM HIGH-PERFORMANCE	RANDOM	< 90K	EITHER	PRESS	CFPA ⩾3°	NO	TNAV INELIGIBLE	YES	YES	ATC METERING
RANDOM LOW-PERFORMANCE	RANDOM	N/A	N/A	UNPRESS	N/A	NO	TNAV INELIGIBLE	NO	NO	RANDOMLY BY TRAFFIC PREPROC

Figure 9 - Traffic Preprocessor Airplane Categories

AIRCRAFT ID	TYPE	ENTRY POINT	EP TIME	ORIGIN	DEPT TIME	FLIGHT TIME	METER FLAG	GROSS WEIGHT	CRUISE ALTITUDE	CRUISE SPEED (KTAS)	CRUISE SPEED M	EQUP. TYPE	EP-MF DIST (NM)
RH 6	JET	EP14	832.62	ATL	630.91	175.	0	0.00	31000.	387.35	.660		284.
BH 701	JET	EP41	844.05	GCC	824.55	90.	2	0.00	29000.	378.88	.640		130.
RH 7	JET	EP16	857.19	MCI	831.64	93.	0	0.00	28000.	374.56	.630		363.
RH 11	JET	EP14	858.51	TPA	611.81	220.	0	0.00	31000.	387.35	.660		284.
RH 8	JET	EP21	907.61	MSP	830.29	115.	0	0.00	28000.	374.56	.630		422.
CO 408	727	EP08	909.23	SAN	825.98	125.	0	133811.49	37000.	446.07	.778	4D	515.
RH 4	JET	EP18	909.73	MLI	830.05	114.	0	0.00	28000.	374.56	.630		401.
WA 455	727	EP39	910.74	FSD	848.10	85.	1	145126.25	35000.	441.84	.766		385.
FL 912	JET	EP32	911.03	COD	841.76	90.	1	0.00	29000.	378.88	.640		310.
CO 30	727	EP07	913.16	LAX	816.02	130.	0	131724.53	37000.	445.15	.776		448.
CO 264	727	EP05	914.54	SFO	808.82	135.	0	142730.69	37000.	450.01	.784		426.
TW 457	767	EP16	917.68	STL	805.74	128.	0	230642.40	39000.	465.78	.812		363.
CO 86	727	EP07	920.44	ONT	833.16	120.	0	134188.48	37000.	446.24	.778		448.
RW 22	737	EP03	922.64	BOI	848.37	90.	0	95574.86	33000.	405.53	.697		298.
WA 55	737	EP28	923.84	BIL	911.07	77.	1	95628.01	33000.	405.56	.697		366.
JC 759	JET	EP69	924.15	WHR	915.57	30.	2	0.00	15000.	313.29	.500		-0.
UA 162	727	EP08	926.04	SAN	842.40	125.	0	139461.20	37000.	448.57	.782	4D	515.
FL 850	JET	EP17	926.13	JAC	846.73	94.	1	0.00	27000.	370.18	.620		265.
FL 137	737	EP12	928.61	DFW	828.87	110.	0	99935.14	35000.	417.49	.724		285.
UA 892	727	EP05	929.06	OAK	828.23	130.	0	144691.28	37000.	450.88	.786		426.
RH 10	JET	EP16	929.39	STL	823.83	133.	0	0.00	28000.	374.56	.630		363.
WA 480	727	EP09	931.07	PHX	908.12	90.	0	149442.78	37000.	452.98	.790		412.
UA 874	727	EP07	932.75	ONT	842.82	122.	0	145163.31	37000.	451.09	.786		448.
WA 295	727	EP21	932.98	MSP	850.74	112.	0	150544.32	35000.	424.29	.736		422.
CO 416	727	EP05	933.82	SJC	828.67	135.	0	132574.60	37000.	445.53	.777		426.
RH 5	JET	EP07	933.90	LAX	842.32	135.	0	0.00	29000.	378.88	.640		448.
RH 14	JET	EP14	934.47	MIA	632.76	235.	0	0.00	31000.	387.35	.660		284.
AP 414	JET	EP26	935.16	ASE	925.02	35.	2	0.00	17000.	323.32	.520		3.
UA 160	767	EP04	937.93	RNO	840.65	120.	0	225838.08	37000.	420.47	.733	4D	358.
UA 694	727	EP05	938.00	SJC	832.40	135.	0	140706.33	37000.	449.12	.783		426.
UA 154	767	EP05	940.52	SFO	833.80	140.	0	207205.99	37000.	420.36	.733	4D	426.
UA 320	727	EP64	941.18	SLC	921.23	74.	1	129604.68	37000.	444.21	.774		314.
TI 938	737	EP12	941.79	IAH	821.84	131.	0	88856.36	35000.	409.57	.710		285.
TI 980	737	EP64	942.15	SLC	934.31	66.	1	94873.72	33000.	405.04	.696	4D	314.
CO 24	727	EP10	943.42	ELP	903.57	95.	0	136436.49	37000.	447.23	.780	4D	318.
CO 462	727	EP09	944.05	PHX	919.26	92.	0	146527.97	37000.	451.69	.787		412.
UA 632	767	EP05	944.08	SMF	848.35	129.	0	226283.78	37000.	420.47	.733		426.
UA 460	727	EP07	945.65	LAS	914.07	104.	0	139198.76	37000.	448.45	.782		448.
RH 1	JET	EP01	946.11	YEG	836.88	142.	0	0.00	29000.	378.88	.640		386.
DL 523	727	EP12	947.88	DFW	851.07	105.	0	140091.14	35000.	439.66	.763		285.
CO 420	727	EP07	948.41	LAS	922.73	98.	0	141012.64	37000.	449.25	.783		448.
UA 806	727	EP06	948.46	FAT	857.30	121.	0	132800.16	37000.	445.63	.777		426.
FF 103	LOW	RUNWAY	952.35	FTC	922.35	30.	2	0.00	0.	0.00	.000		0.
UA 680	727	EP06	952.94	MRY	854.42	128.	0	139078.93	37000.	448.40	.782	4D	426.

Figure 10 - Sample Input Demand List



1 CLOCK
NOAA
INDICES TO ENTRY
FIX LIST
ARRIVAL METERING
METER FIX TIME
SURVEILLANCE ARRAY SIZES
SURVEILLANCE POSITION DATA
STACK DATA
CONFLICT DATA

2 UPDATED STACK DATA
UPDATED SURVEILLANCE
POSITION DATA
METERFIX COUNT
EXITING A/C DATA

3 CLOCK
GROUND HOLD TIME WINDOW
METERING FLAGS
SYSTEM DELAY
TRAFFIC INPUT FILE NUMBER
MXD, MXG
ENTRY FIX TIMES
POINTERS TO DEMAND LIST
NUMBERS OF A/C ON DEMAND
LIST

4 UPDATED ENTRY FIX TIMES
UPDATED POINTERS TO
DEMAND LIST
GROUND HOLD STATISTICS
GROUND HOLD A/C TYPE
NUMBER OF GROUND HELD A/C
ID OF GROUND HELD A/C
TIME AT RUNWAY FOR
GROUND HELD A/C
TIME SPENT IN GROUND HOLD

5 CURRENT A/C DATA
CLOCK
TRAFFIC INPUT FILE NUMBER
TIME AT ENTRY FIX
POINTERS TO DEMAND LIST

6 UPDATED CURRENT A/C DATA

7 NUMBERS OF CURRENT A/C
ARAYEF
ARRIVAL METERING POSITION
DATA
METERING FLAGS
HIGH PERFORMANCE ARRIVAL
METERING DATA
LOW PERFORMANCE ARRIVAL
METERING DATA
PATH ID
CLOCK
AIRPORT DATA
ARRIVAL METERING DATA

8 A/C DELAY
SYSTEM DELAY
FREEZE FLAG
NUMBER OF PLANES OVER
ENTRY POINT
NUMBERS OF EXITING A/C

9 FREEZE FLAG
ARRIVAL METERING METER
FIX TIME
A/C DELAY
SYSTEM DELAY
CLOCK
NUMBER OF ACTIVE A/C
EQUIPAGE OF ACTIVE A/C
STACK DATA
PRESENT ALTITUDE
MXA, MXH
A/C ID
PATH ID
TIME AT METER FIX
DELAY CONTROL DATA

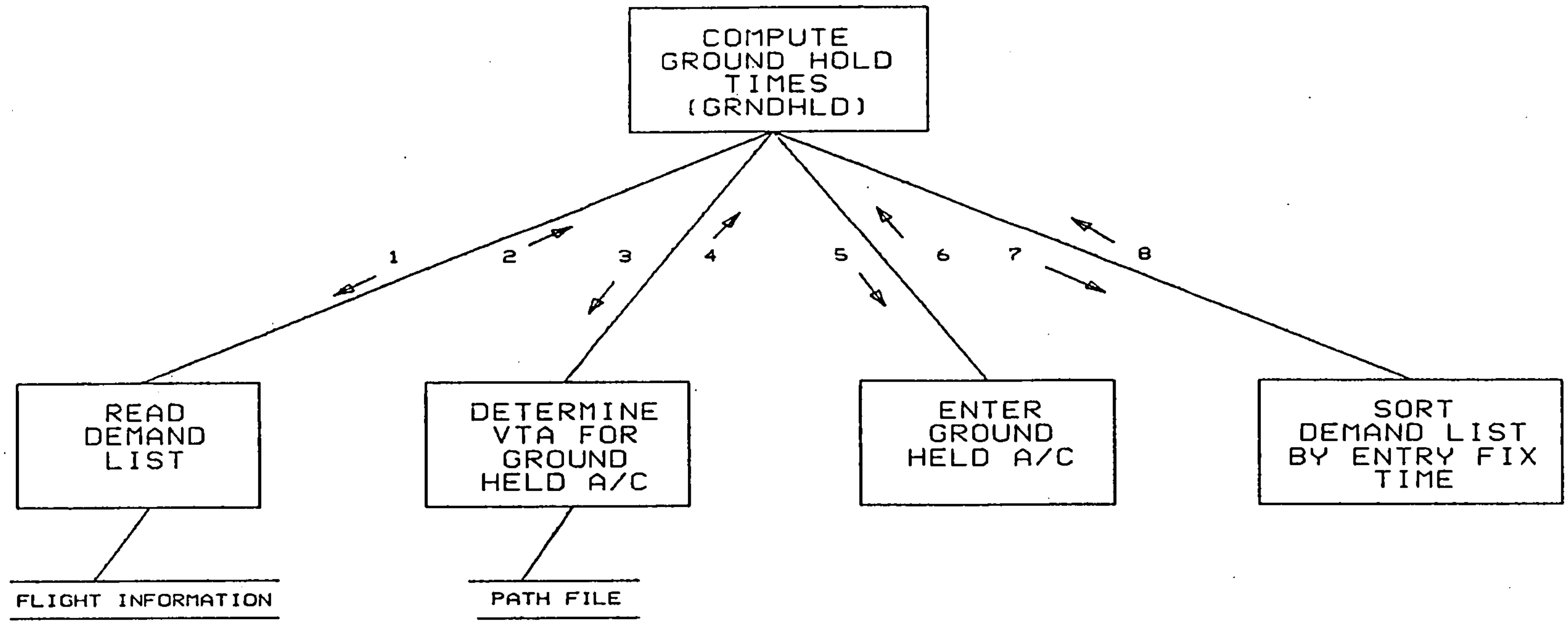
10 HOLDING DATA
VECTORING DISTANCE
CLEARANCE STATISTICS
SPEED REDUCTIONS

11 ARAYEF
CLOCK
NUMBER OF ACTIVE A/C
NUMBER OF NEW A/C
A/C DELAY
TIME AT METER FIX
ARRIVAL METERING METER
FIX TIME
HOLDING DATA
SPEED REDUCTIONS
VECTORING DISTANCE
A/C ID
MXWPT, MXSEG, MXNOAA

13 NUMBER OF ACTIVE A/C
ARAYEF
CONFLICT POSITION DATA
MXA, MXC
ATC SEPARATIONS
EQUIPAGE
A/C ID
CLOCK
CONFLICT DATA

14 UPDATED CONFLICT DATA

Figure 11 - Air Traffic Control Module



1 TRAFFIC INPUT FILE NUMBER

2 FLIGHT INFORMATION

3 ENTRY FIX NAME
WAYPOINT ARRAY
DISTANCE ARRAY
CRUISE SPEED
MAXIMUM ALTITUDE

4 VTA OF GROUND HELD A/C

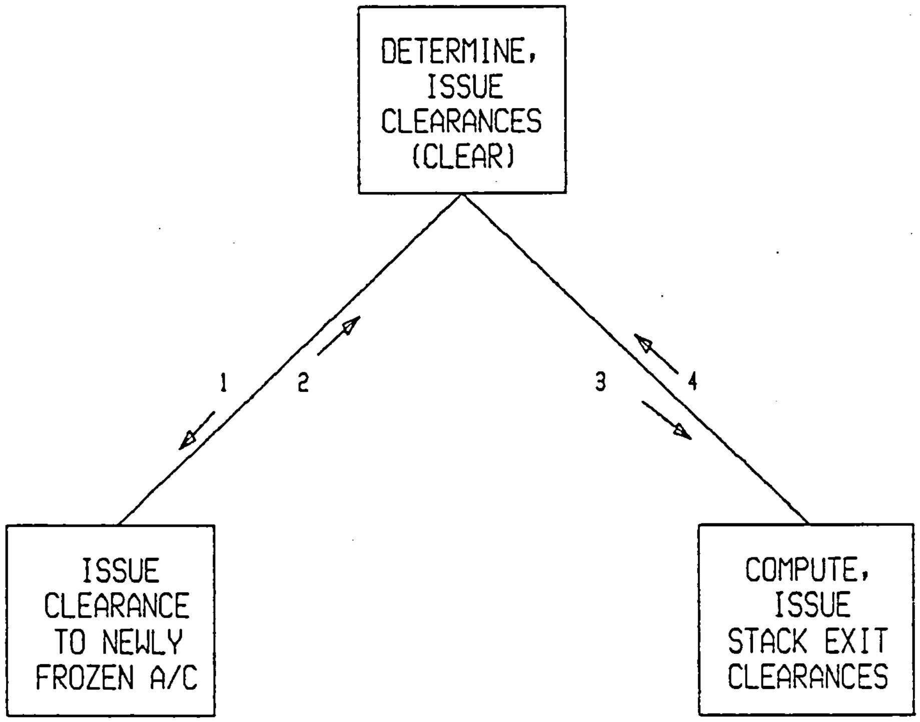
5 METERING FLAGS
NUMBER OF A/C ON DEMAND LIST
POINTERS TO DEMAND LIST
DEPARTURE TIME
CLOCK
GROUND HOLD TIME WINDOW
GROUND HOLD TIMES
NOGH
ENTRY FIX TIMES
FLIGHT INFORMATION

6 UPDATED NOGH
UPDATED GROUND HOLD TIMES
UPDATED ENTRY FIX TIMES
GROUND HOLD ID'S
GROUND HOLD LIST DATA
GROUND HOLD STATISTICS
GROUND HOLD A/C TYPE

7 NUMBER OF A/C ON DEMAND LIST
POINTERS TO DEMAND LIST

8 UPDATED POINTERS TO DEMAND LIST

Figure 12 - Ground Hold Processing Module



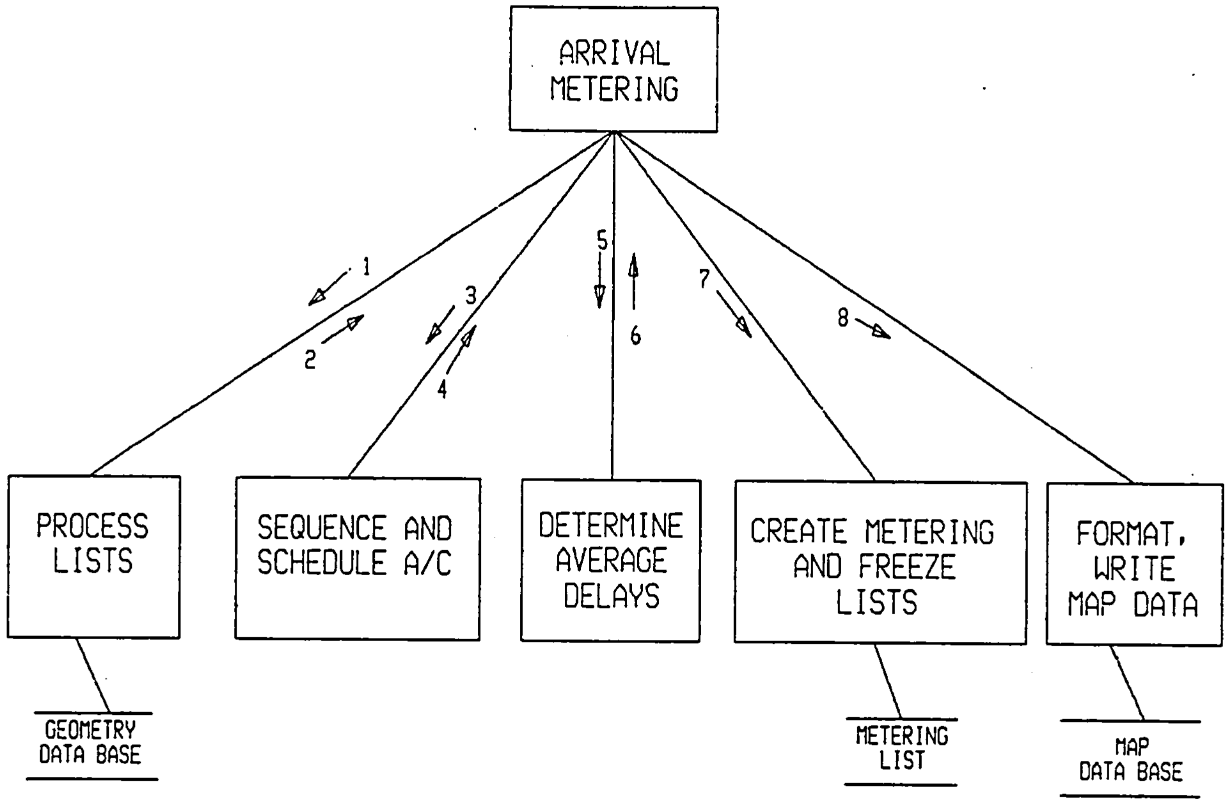
1 EQUIPAGE
ARRIVAL METERING METER FIX TIME
DELAY CONTROL DATA
A/C DELAY

2 HOLDING DATA
CLEARANCE STATISTICS
ATC METER FIX TIME
SPEED REDUCTIONS
VECTOR DISTANCE

3 NUMBERS OF A/C IN EACH STACK
EQUIPAGE
ARRIVAL METERING METER FIX TIME

4 HOLDING DATA
ATC METER FIX TIME
CLEARANCE STATISTICS

Figure 13 - ATC Clearance Module



1 LIST DATA
ARRIVAL-METERING DATA

2 PRIORITY-ORDERED
LANDING LIST
DATA
FREEZE FLAG
LPFRZ FLAG
DELAY DATA
METERING LIST
DATA
MAPPING NUMBERS
TRANSITION TIME
NUMBERS OF EXITING A/C

3 PRIORITY-ORDERED
LANDING LIST
DATA
AIRPORT DATA
CLOCK TIME
NUMBERS OF A/C
VTA'S
TRANSITION TIME
FREEZE FLAG
LPFRZ FLAG

4 CLT'S
MFT'S
DELAY PARAMETERS

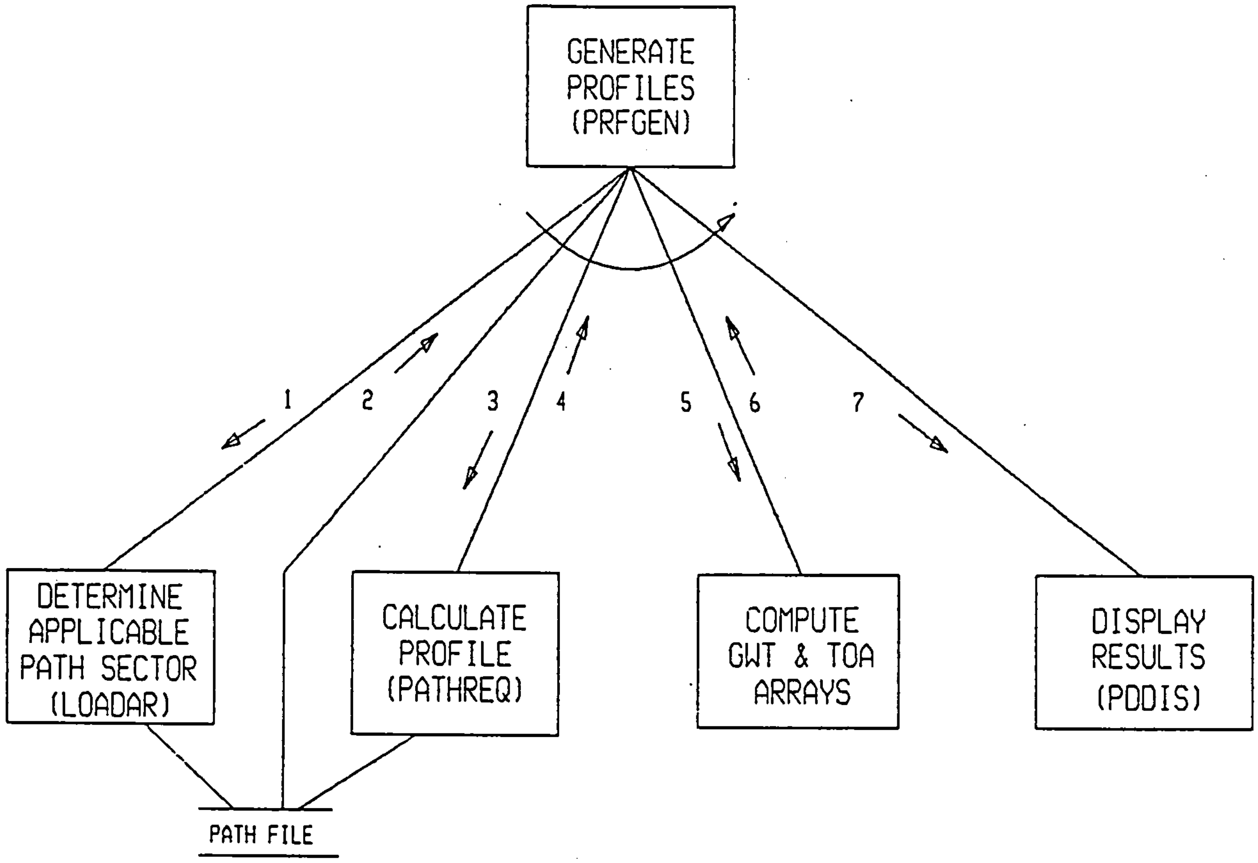
5 DELAY PARAMETERS

6 SYSTEM DELAY

7 PRIORITY-ORDERED
LANDING LIST
DATA
METERING LIST
DATA
VTA'S
CLT'S
A/C ID
FREEZE LIST
RUNWAY

8 MAP DATA

Figure 14 - Arrival Metering Module



1 HOLDING DATA
ATC METER FIX TIME
CLOCK
INDEX TO ENTRY FIX LIST
VECTOR DISTANCE
SPEED REDUCTIONS
NEW A/C FLAG

2 WAYPOINT NUMBERS
DESCENT MACH

3 WAYPOINT NUMBERS
DESCENT MACH
HOLDING DATA
ATC METER FIX TIME
SPEED REDUCTIONS
VECTOR DISTANCE
CLOCK
A/C DELAY
MXWPT, MXSEG
INDEX TO ENTRY FIX LIST

4 -------

5 GWT ARRAY
TOA ARRAY
SEGMENT FUEL ARRAY
SEGMENT TIME ARRAY
WAYPOINT NUMBERS
MXWPT, MXSEG

6 UPDATED GWT ARRAY
" TOA ARRAY
" SEGMENT FUEL ARRAY
" SEGMENT TIME ARRAY
" WAYPOINT NUMBERS
" MXWPT, MXSEG

7 HOLDING DATA
FINAL WAYPOINTS
ASSIGED METER FIX
DESCENT MACH
ATC METER FIX TIME
ENTRY POINT NAME
SPEED REDUCTIONS
VECTOR DISTANCE
A/C ID
ARRIVAL METERING METER FIX TIME
WAYPOINT NUMBERS

Figure 15 - Profile Generation Module

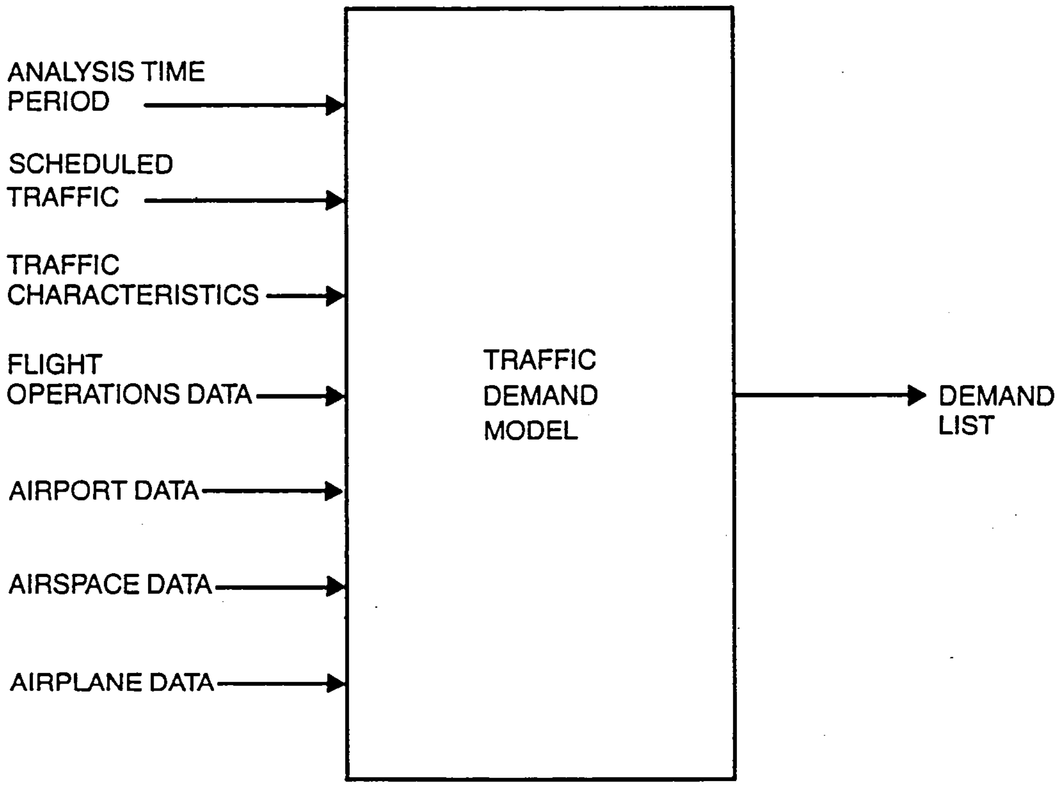


Figure 16 - Traffic Demand Model Data Requirements

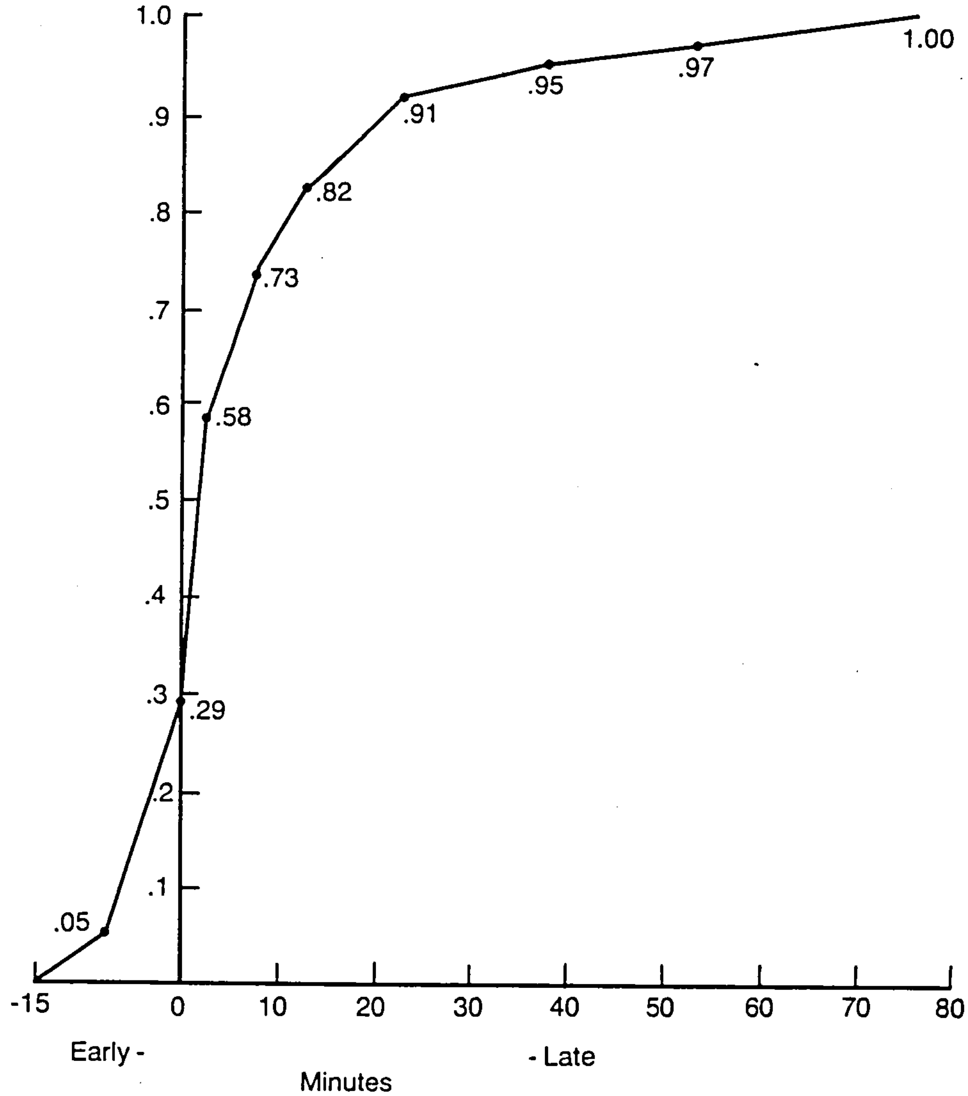


Figure 17 - Runway Lateness Distribution for Denver

TRAFFIC PREPROCESSOR

- SELECTION OF SCHEDULED TRAFFIC FROM OAG
- GENERATION OF RANDOM TRAFFIC
- ASSIGNMENT OF COMMERCIAL JET EQUIPAGE
- DETERMINATION OF ENTRY POINT CHARACTERISTICS
    - ALTITUDE
    - SPEED
    - ENTRY POINT TIME
    - GROSS WEIGHT (COMMERCIAL JETS ONLY)
- CONSTRUCTION OF DEMAND LIST

Figure 18 - Traffic Model Functional Architecture

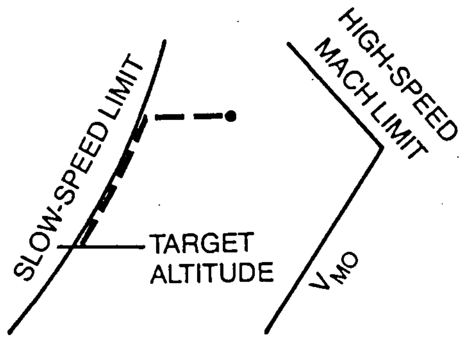
ENGINE DATA

- **FUEL FLOW TABLES**
  - IDLE FUEL FLOW VS MACH, ALTITUDE
  - NON-IDLE TSFC VS NORMALIZED THRUST, MACH, ALTITUDE
- **EPR TABLES**
  - EPR VS CORRECTED N_1, MACH, ALTITUDE
  - MAX CRUISE EPR VS TAT
  - MAX CLIMB EPR VS TAT
- **THRUST TABLES**
  - IDLE THRUST VS MACH, ALTITUDE
  - INSTALLED NET THRUST VS EPR, MACH
    - NET THRUST CORRECTION VS MACH, ALTITUDE

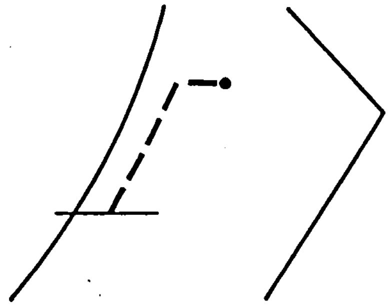
Figure 19 - Engine Data Base Architecture

- **AIRFRAME DATA**
  - **GROSS WEIGHTS**
    - MINIMUM ZERO-FUEL WEIGHT
    - MAXIMUM OPERATING WEIGHT
  - **SPEED LIMITS**
    - SLOW SPEED
      - FLAP EXTENSION
      - SLOW SPEED MACH BUFFET VS ALTITUDE, WEIGHT
    - FAST SPEED
      - MAXIMUM OPERATING MACH
      - MAXIMUM OPERATING EQUIVALENT AIRSPEED
      - THRUST-LIMITED TRUE AIRSPEED VS WEIGHT, ALTITUDE, TEMPERATURE
      - HIGH-SPEED MACH BUFFET VS ALTITUDE, WEIGHT
  - **WING AREA**
  - **NUMBER OF ENGINES**
  - **SERVICE CEILING ALTITUDE**
  - **DRAG POLARS**
  - **MAXIMUM C_D VS EQUIVALENT AIRSPEED**

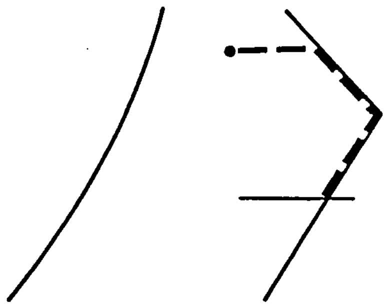
Figure 20 - Airframe Data Base Architecture



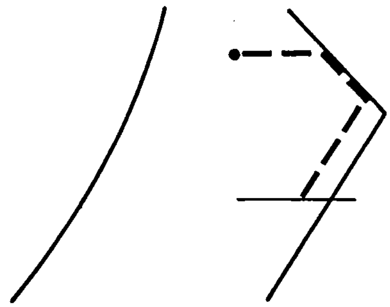
ASSIGNED SPEED LOWER THAN OR EQUAL TO SLOW-SPEED LIMIT



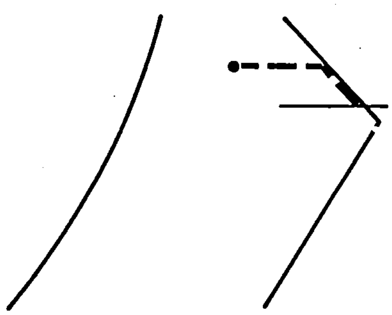
ASSIGNED SPEED WITHIN FLIGHT ENVELOPE



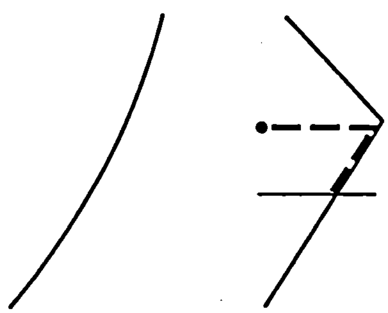
ASSIGNED SPEED GREATER THAN OR EQUAL TO V_{MO}



ASSIGNED SPEED LESS THAN V_{MO} WHEN TARGET ALTITUDE BELOW HIGH-SPEED CROSSOVER



ASSIGNED SPEED GREATER THAN HIGH-SPEED LIMIT AT TARGET ALTITUDE, WHICH IS ABOVE CROSSOVER



ASSIGNED SPEED GREATER THAN V_{MO} WHEN STARTING ALTITUDE BELOW CROSSOVER

Figure 21 - Descent Speed Schedules in Response to ATC Speed Clearances

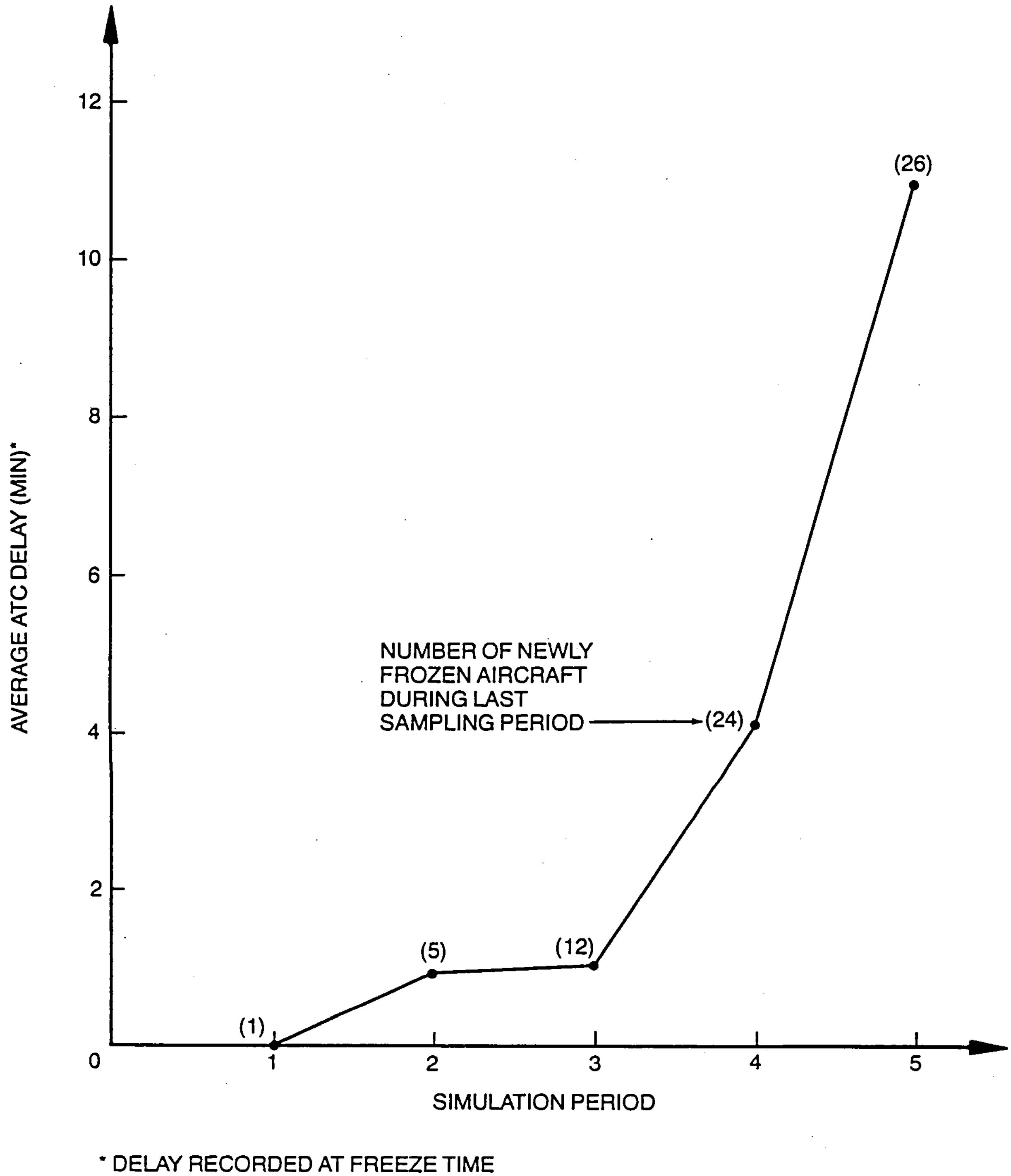


Figure 22 - ATC Delays by Sampling Period

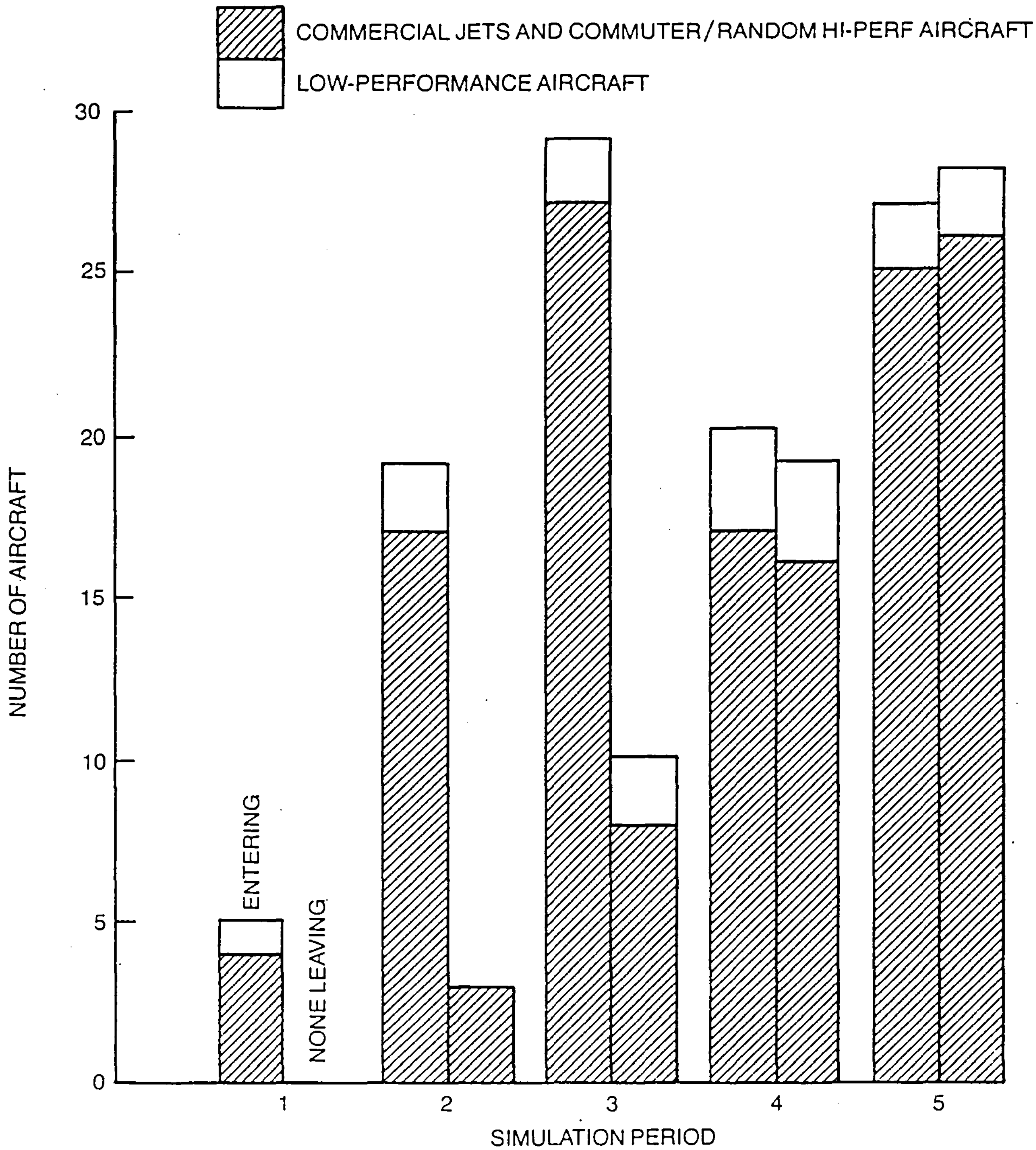


Figure 23 - Number of Aircraft Entering and Leaving Simulation

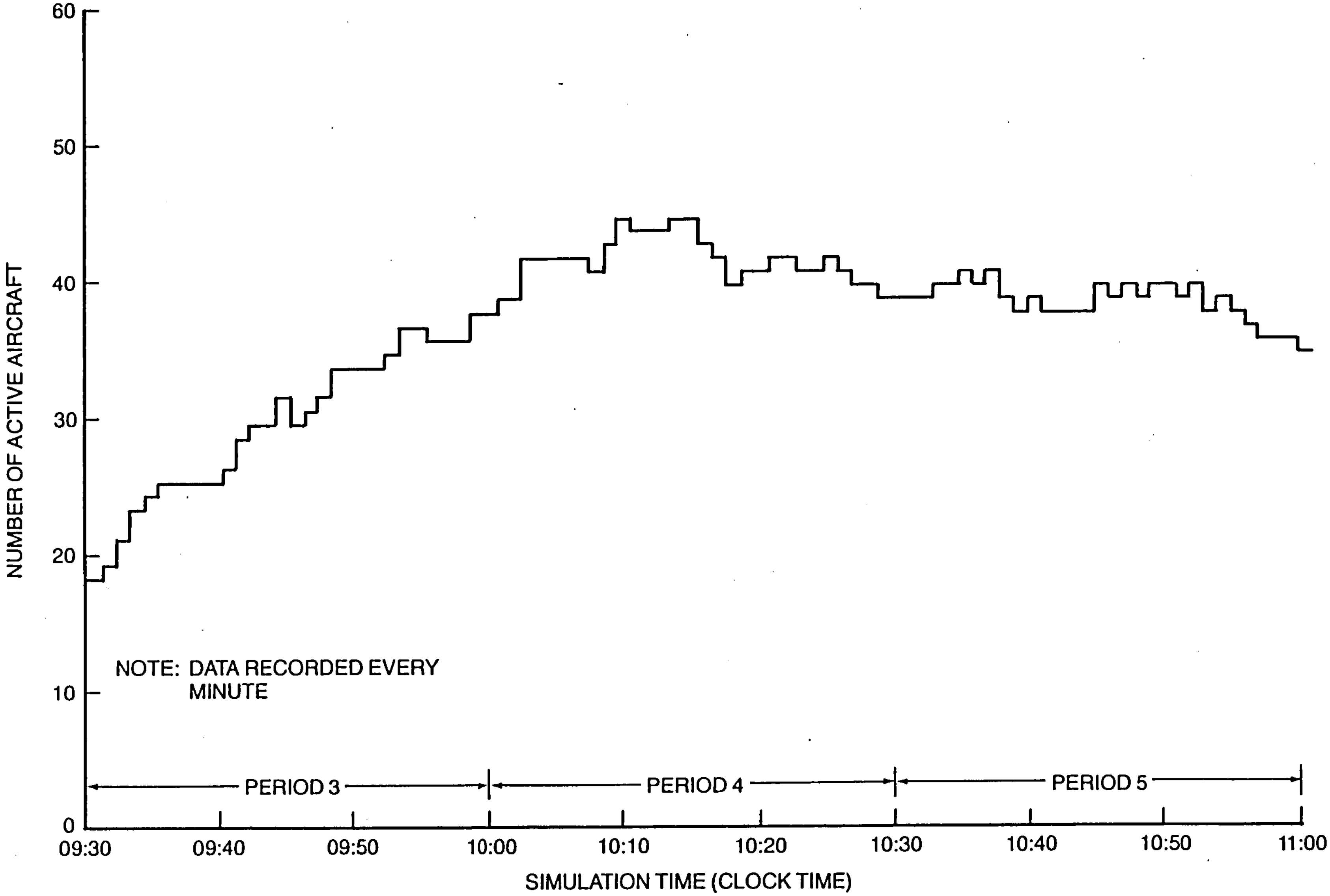


Figure 24 - Number of High-Performance Aircraft Processed by the Simulation

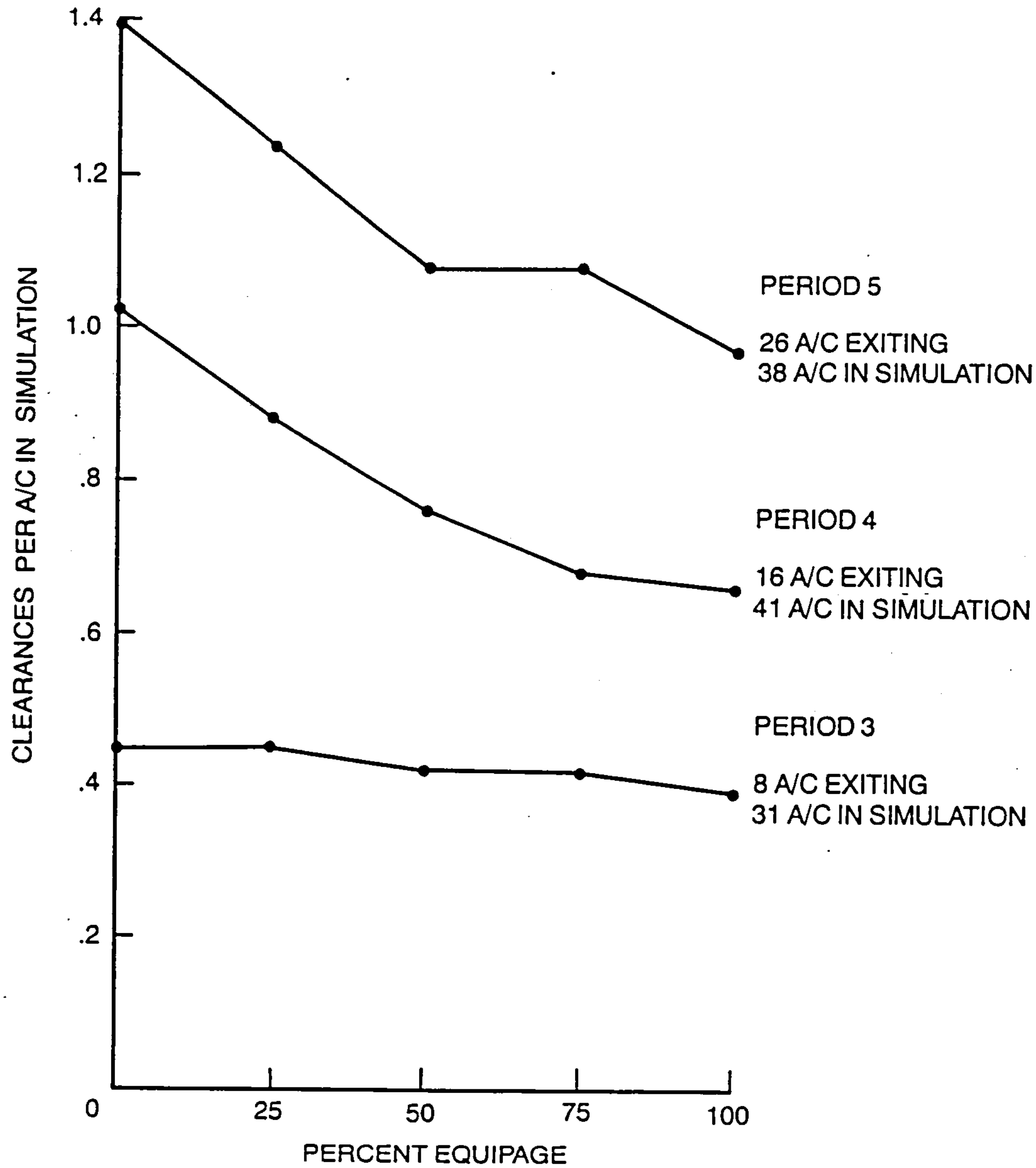


Figure 25 - Workload at Various Equipages and Traffic Levels

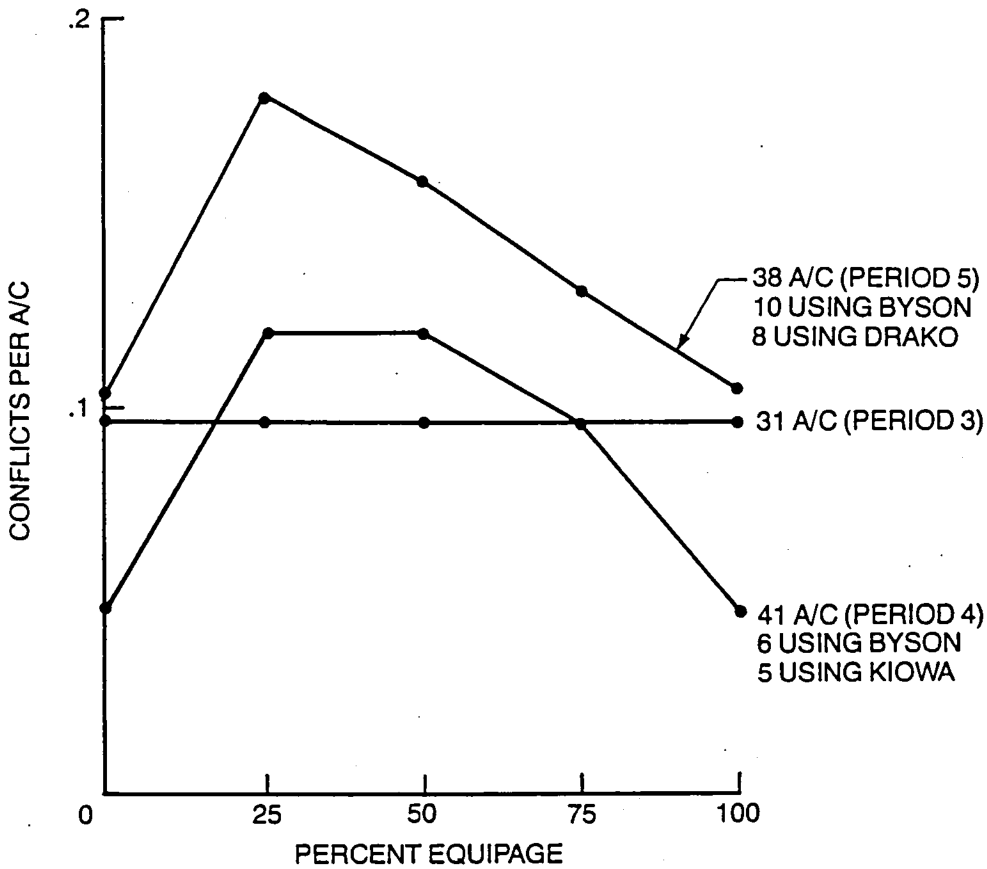


Figure 26 - Conflict Rate of Various Equipages and Traffic Levels

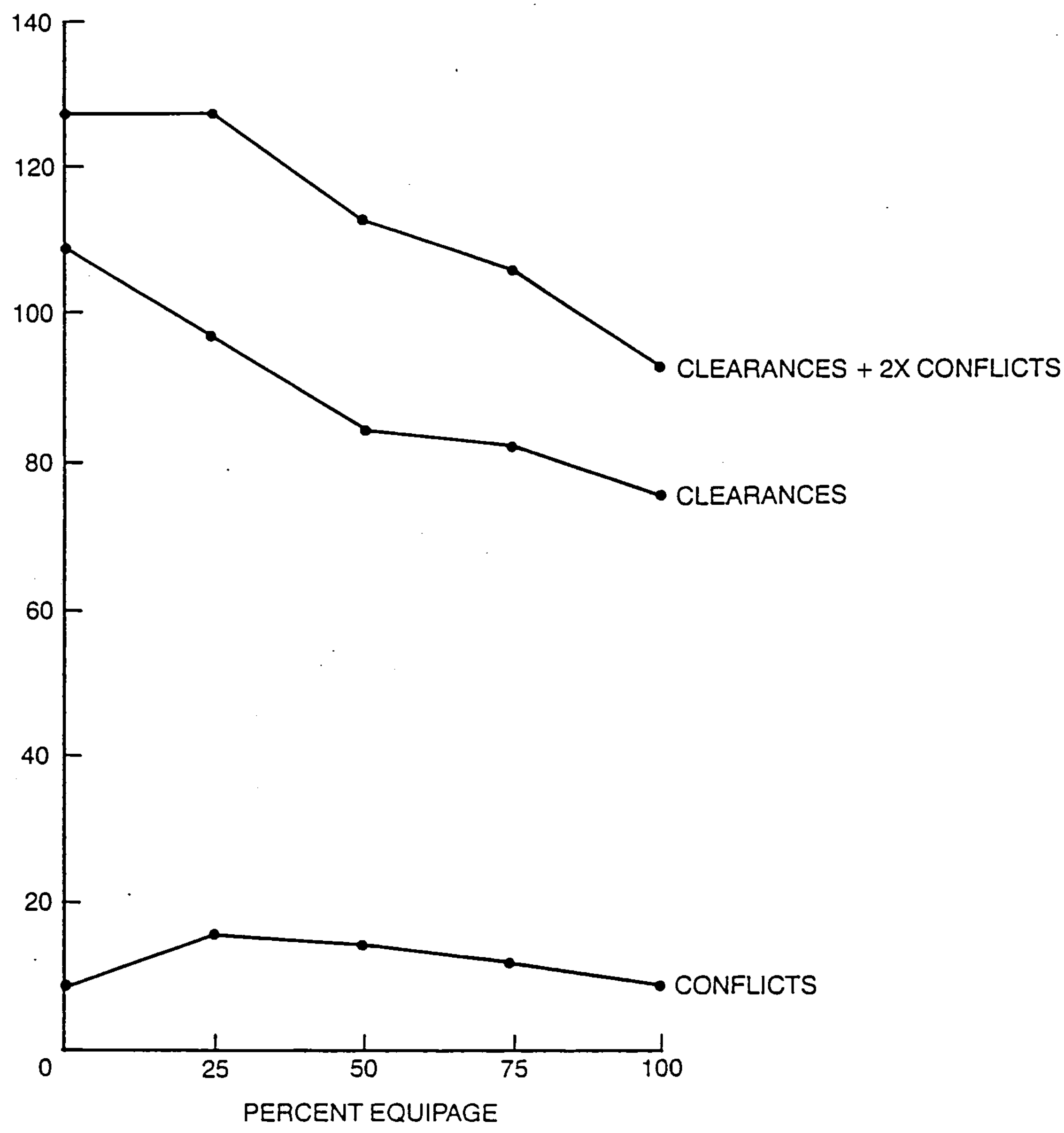


Figure 27 - Summary of Clearances and Conflicts

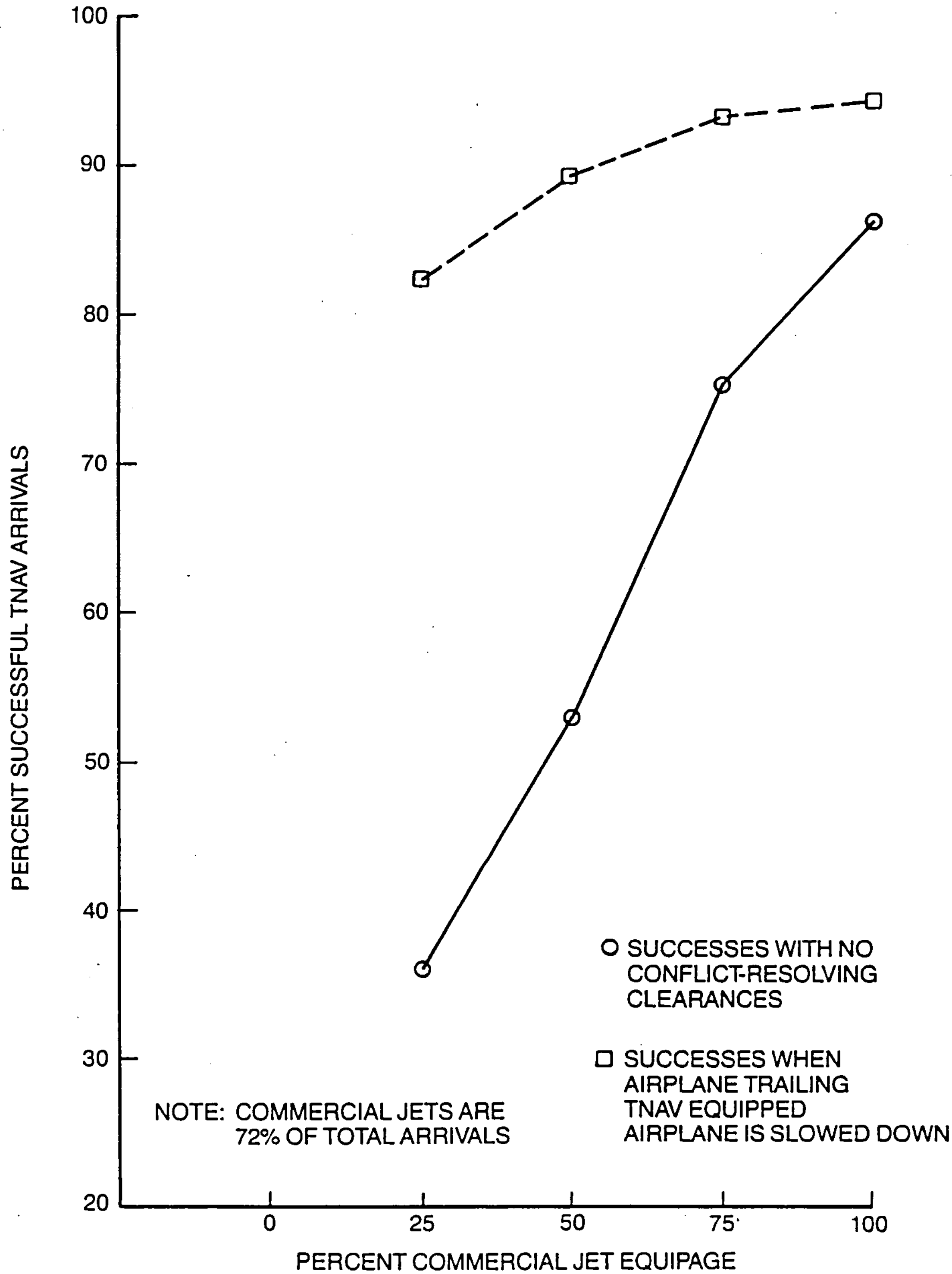


Figure 28 - Probabilities of Successful TNAV Arrivals

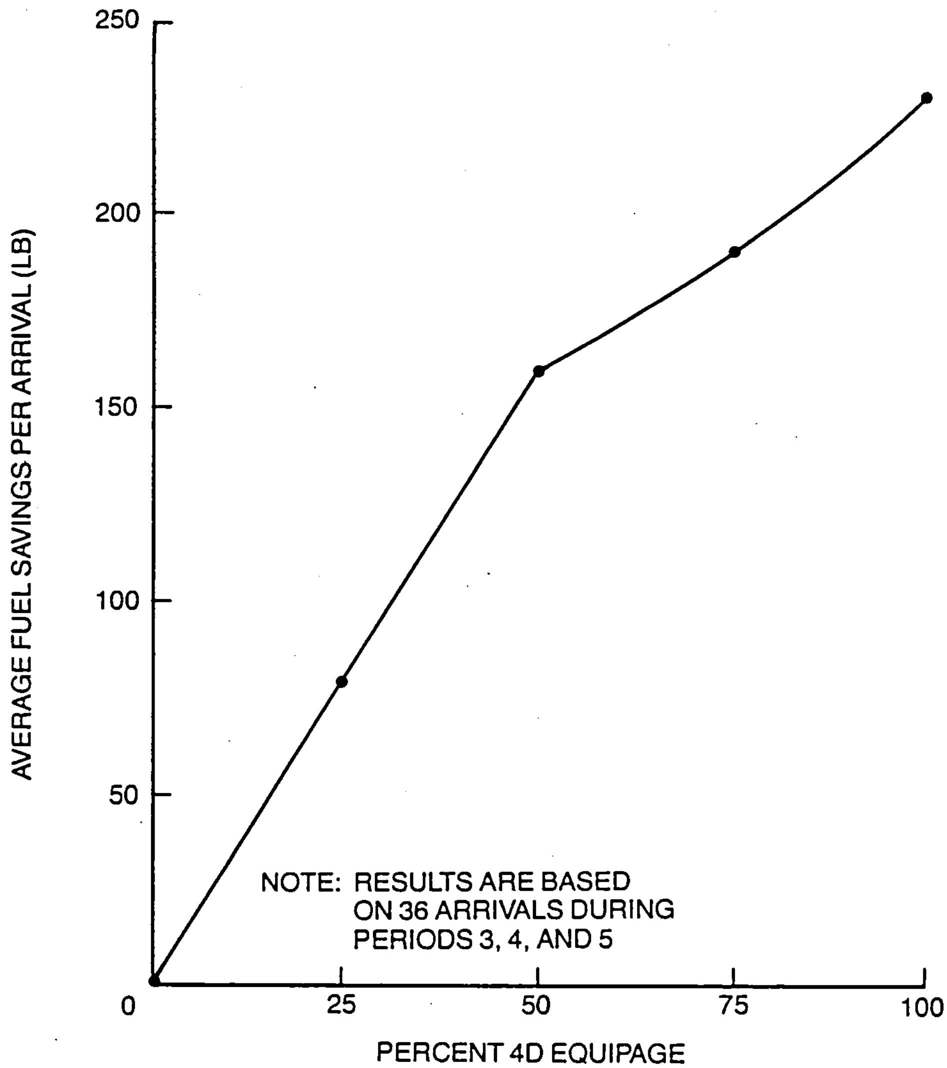


Figure 29 - TNAV Fuel Savings vs Percent Equipage, Averaged Over Entire Fleet

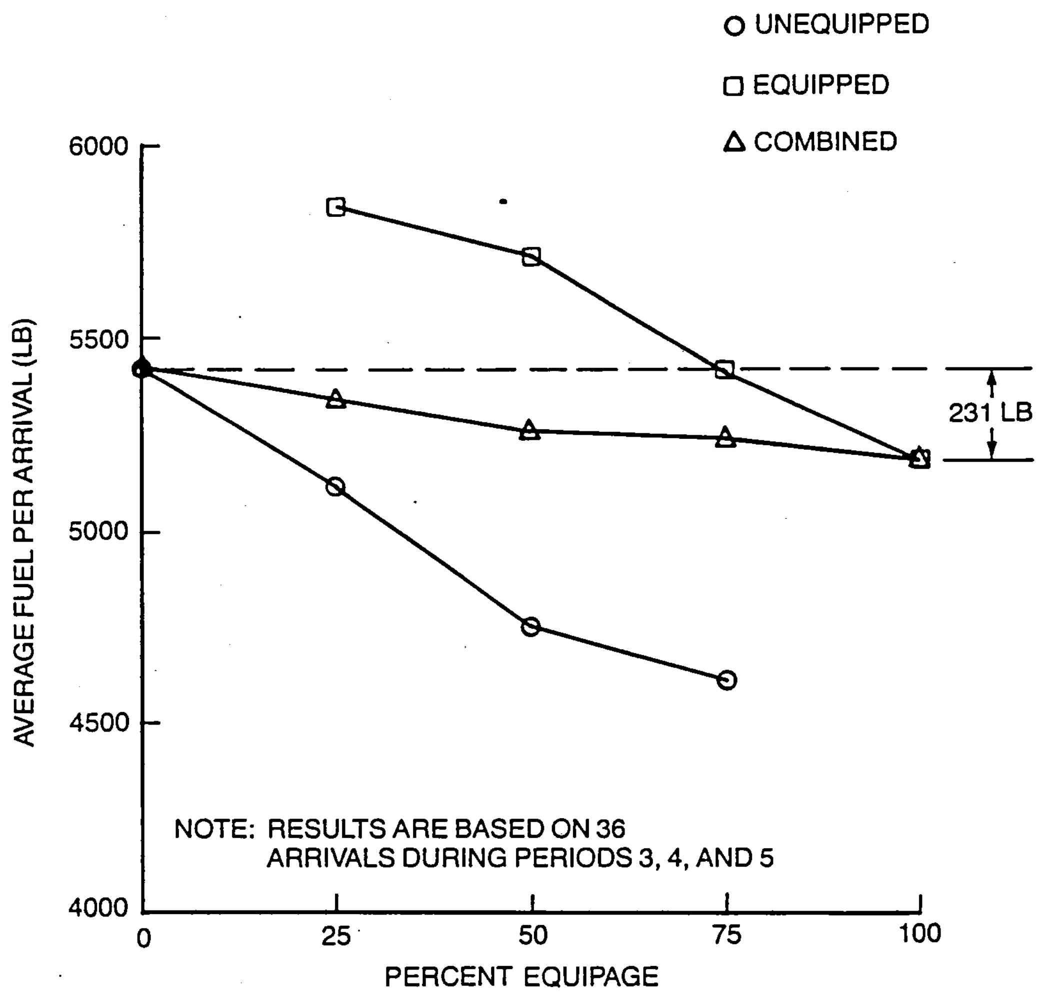


Figure 30 - Comparison of Equipped and Unequipped Average Fuel as a Function of Percent Equipage

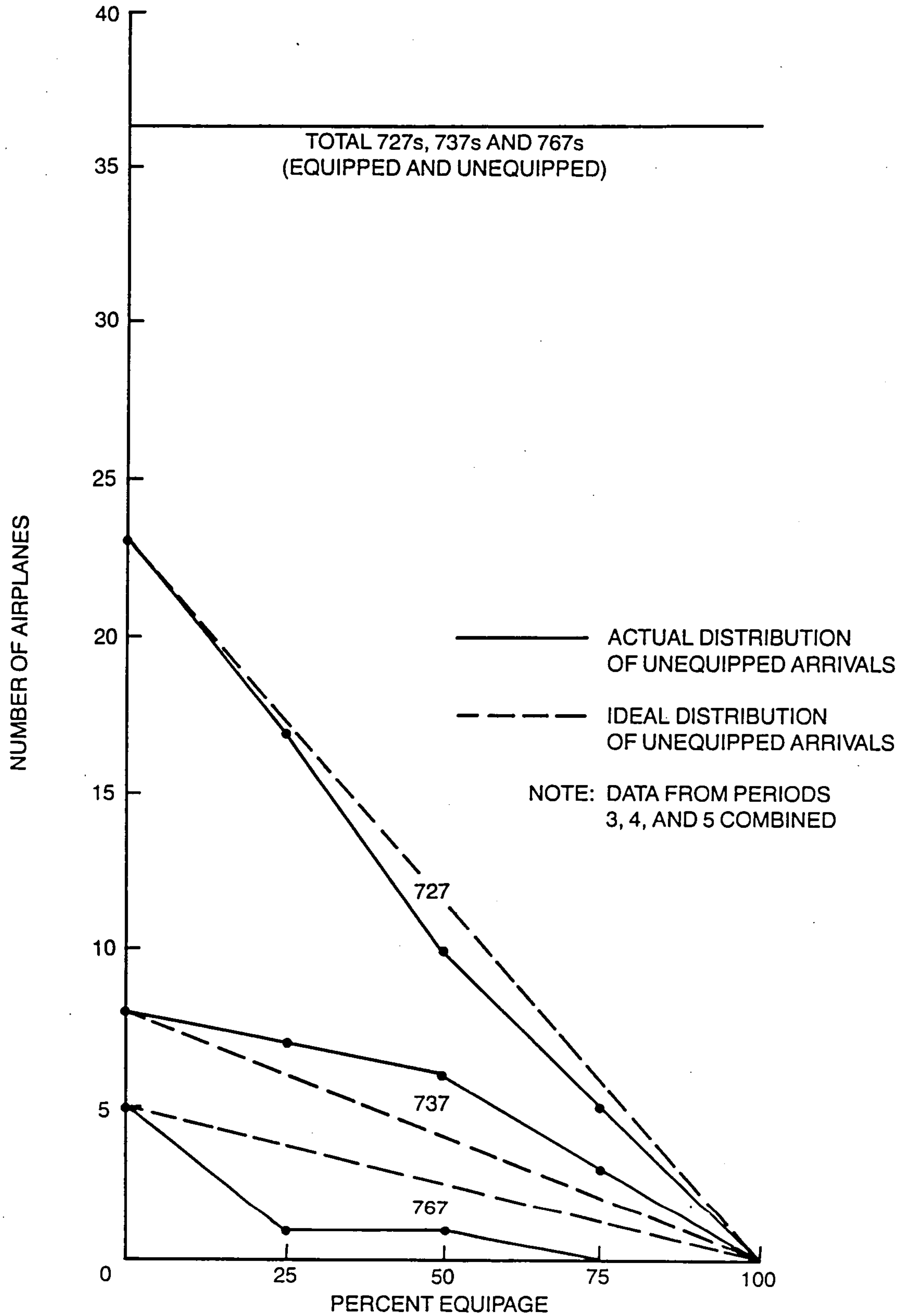


Figure 31 - Distribution of Airplane Types With Level of TNAV Equipage

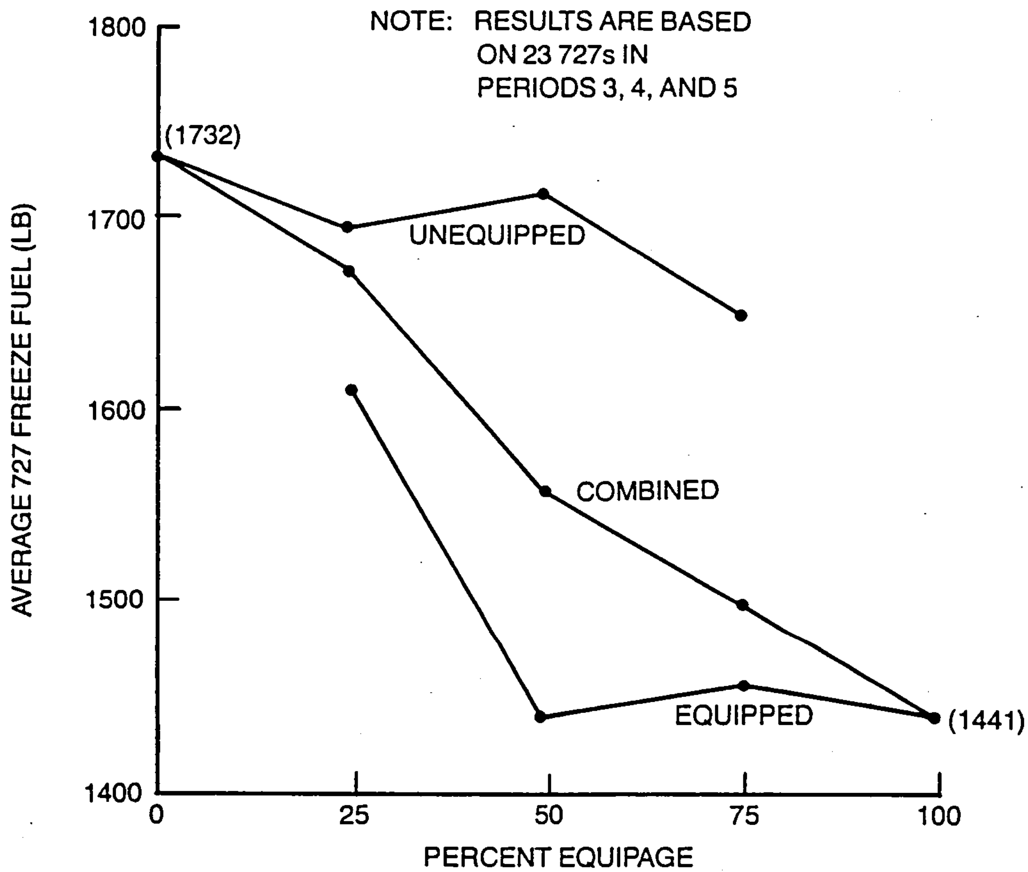


Figure 32 - Average 727 Freeze Fuel vs Equipage Level

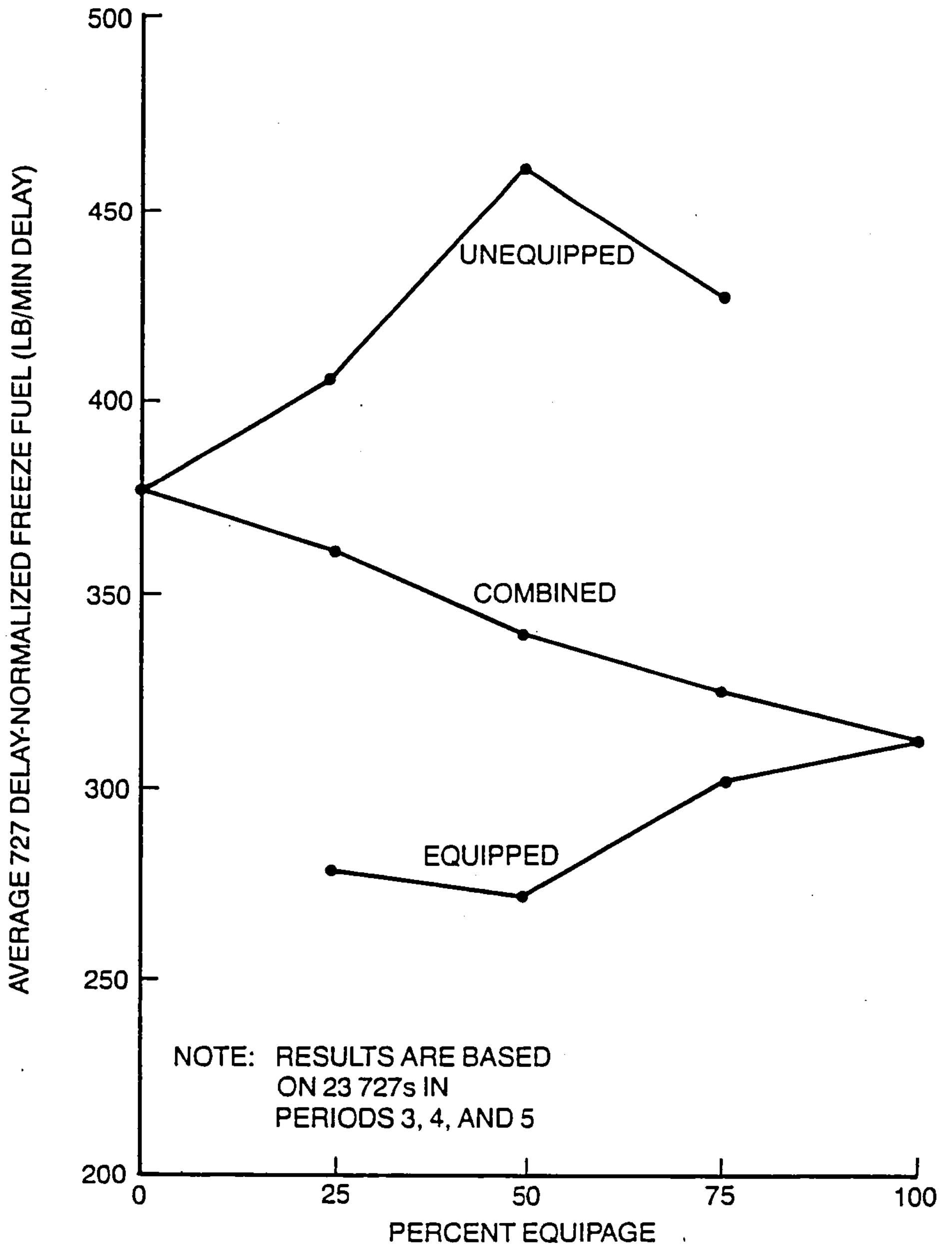


Figure 33 - Average 727 Delay—Normalized Freeze Fuel vs Equipage Level

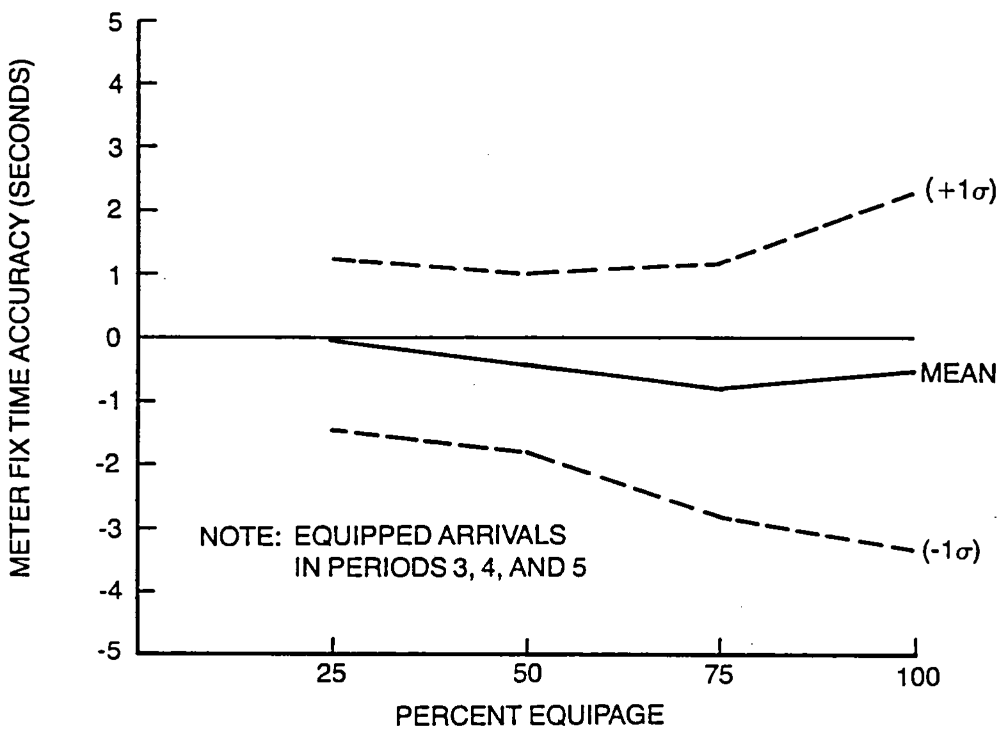


Figure 34 - Mean Meter Fix Arrival Time Accuracy vs Percent Equipage for Equipped Arrivals

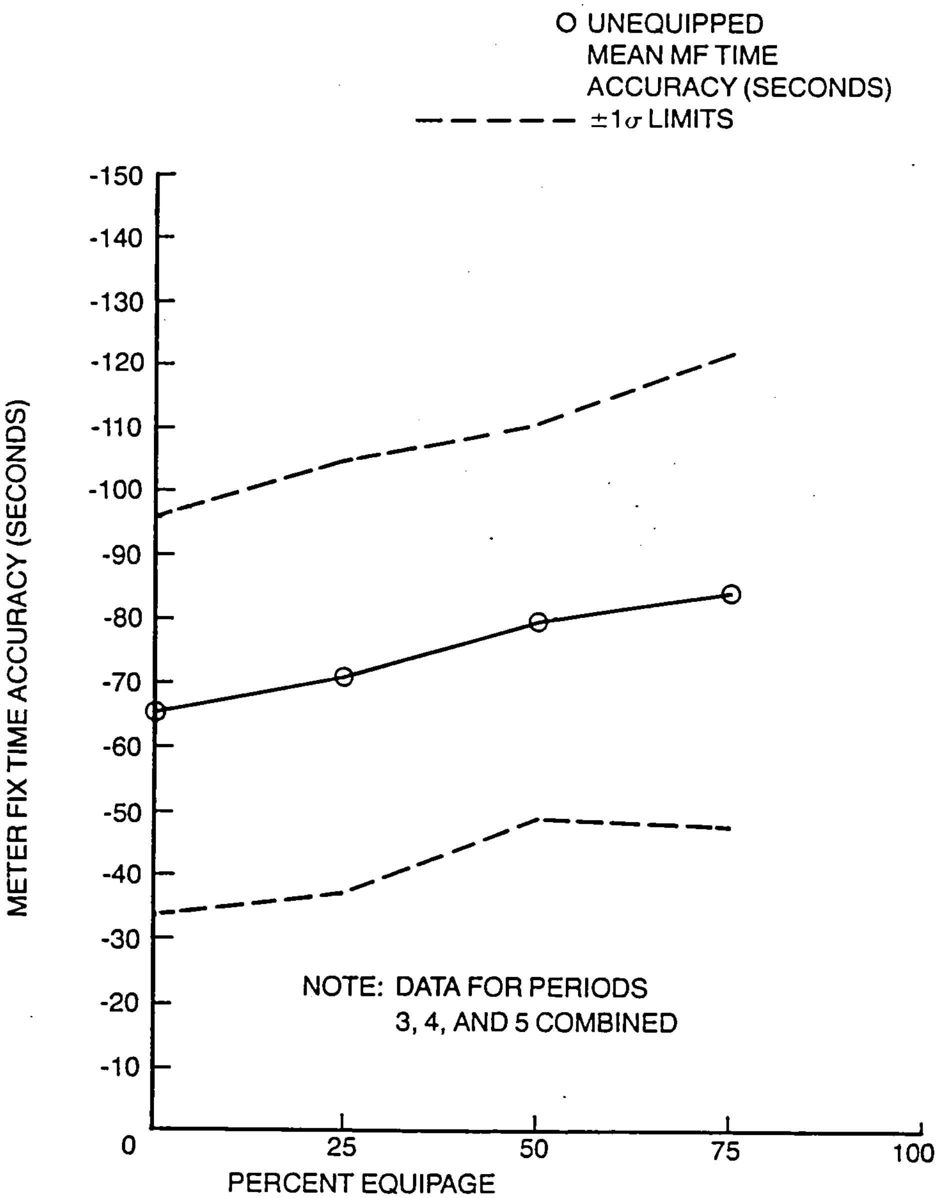


Figure 35 - Mean Meter Fix Arrival Time Accuracy vs Percent Equipage for Unequipped Arrivals

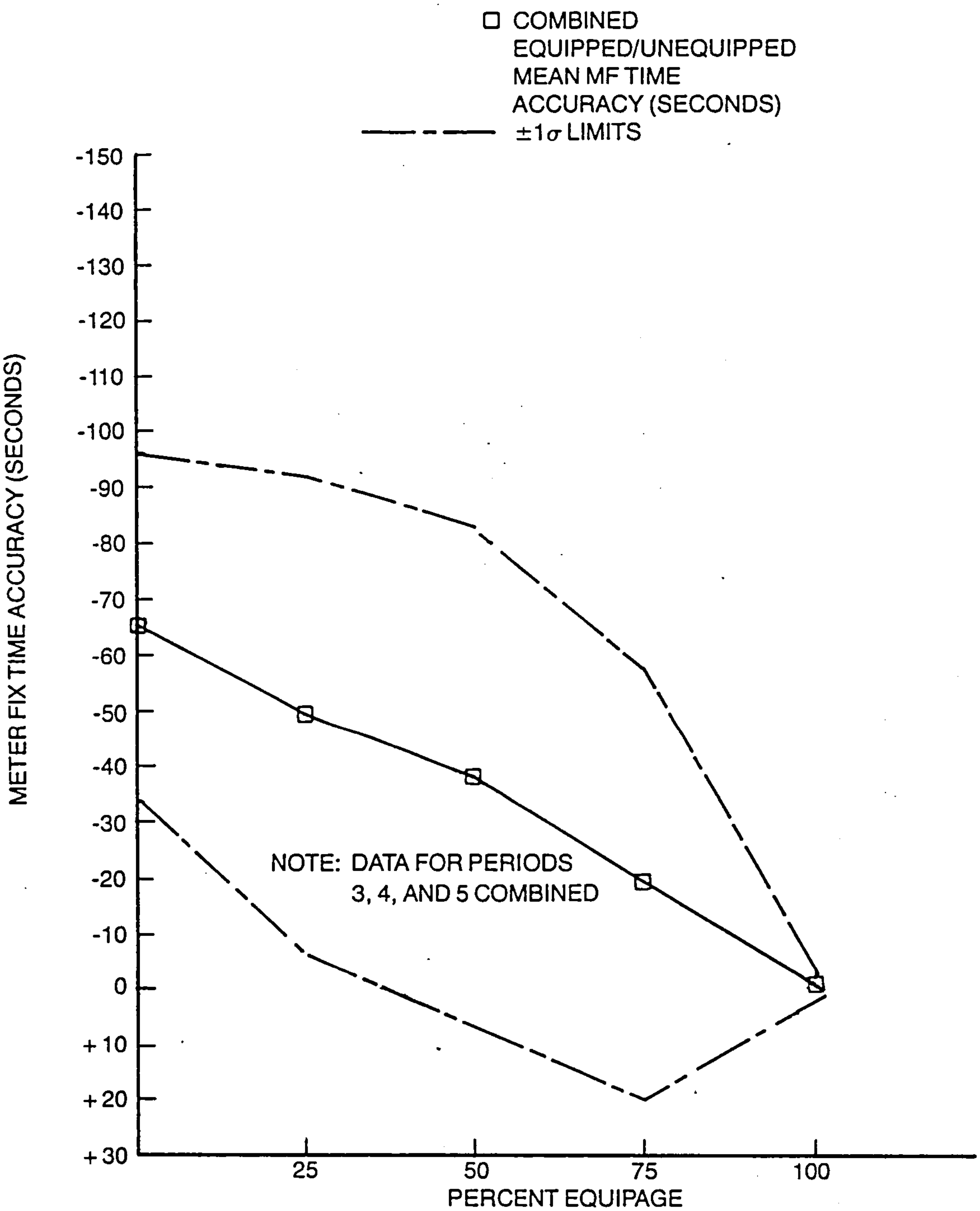


Figure 36 - Mean Meter Fix Arrival Time Accuracy vs Percent Equipage for Combined Equipped/Unequipped Arrivals

Table 1. Terminal Area Transition Data, Four Denver Runways

Runway	Meter fix	Transition time[a] (min)	Distance (nmi)
35	KEANN	13.3	56
	KIOWA	12.4	42
	DRAKO	12.8	58
	BYSON	10.0	42
26	KEANN	10.1	42
	KIOWA	9.3	40
	DRAKO	11.6	52
	BYSON	12.5	56
17	KEANN	10.1	42
	KIOWA	13.1	54
	DRAKO	9.2	38
	BYSON	10.3	54
8	KEANN	12.0	54
	KIOWA	11.2	50
	DRAKO	11.1	46
	BYSON	10.1	42

[a]Assumes calm wind

Table 2. Arrival Aircraft Lateness[a] Distribution

Amount of time late or early	Percent of flights late or early (%)
More than 15 min early	0
Less than 15 min early	5
On time	24
Less than 5 min late	29
5 to 10 min late	15
10 to 15 min late	9
15 to 30 min late	9
30 to 45 min late	4
45 to 60 min late	2
More than 60 min late	3

(Table copied from "Stapleton International Airport Data Package No. 2," Peat, Marwick, Mitchell & Co., June 1978.)

[a]Average deviation from schedule, excluding delays due to destination airport

Table 3. Landing Weight Distribution[a] and Fuel Burn by Airplane type

Boeing airplane type	Mean weight (lb)	Standard deviation (lb)	Average[b] fuel burn (lb/nmi)
707-320C	205,400	10,270	27
727-200	132,960	6,650	19
737-200	88,290	4,410	15
767-200	241,290	12,060	20

[a]Distribution is assumed to be a truncated normal with limits at $\pm 1\sigma$. Standard deviation is arbitrarily specified as 5% of the mean.

[b]Average fuel burn is used only to estimate gross weight at the entry point.

Table 4. Airline Companies Serving Denver-Stapleton International[a]

Identifier	Airline name
AE	Airborne Express
AP	Aspen Airways, Inc.
BH	Air U.S.
BN	Braniff International Airways
CO	Continental Airlines
CS	Colorado Airlines, Inc
DL	Delta Air Lines, Inc.
EA	Eastern Air Lines, Inc.
FB	Murray Valley Airlines
FF	Fort Collins Flying Service
FL	Frontier Airlines, Inc.
FM	Federal Express
JB	Pioneer Airways, Inc.
JC	Rocky Mountain Airways
KZ	Sterling Air Service, Inc.
MX	Mexicana de Aviacion
OZ	Ozark Air Lines, Inc.
PI	Piedmont Aviation, Inc.
RC	Republic Airlines, Inc.
RW	Hughes Airwest
TI	Texas International Airlines, Inc.
TW	Trans World Airlines
UA	United Airlines, Inc,
WA	Western Airlines, Inc.
ZK	Shavano Air, Inc.
ZR	Star Airways
ZV	Air Midwest

[a]Source: Official Airline Guide, August 1980

Table 5. Airplane Type Equivalency Assignments

Original airplane type	Equivalent Boeing type
Convair 880 DeHavilland Comet 4	727-200
Caravelle Hawker Siddely Trident Douglas DC-9 Tupolev TU-104 Tupolev TU-134	737-200
Illyushin IL-62 Douglas DC-8 Tupolev TU-154	707-320C
Douglas DC-10 Airbus A300 Airbus A310 Lockheed L-1011	767-200

Table 6. OAG-Listed Airplanes Classified as Commuters

All Convair (except Series 880)
DeHavilland Canada DHC-7
Handley Page Jet Stream
Swearingen Metro
Aerospatiale Corvette

Table 7. OAG-Listed Airplanes Classified as Low-Performance

All Piston Series Cessnas
DeHavilland Canada Twin Otter
DeHavilland Canada DHC-6
Beech 99
Piper Aero Star 601

Table 8. Meter Fix Loading of Each Sampling Period

Meter fix name	Simulation period 1	2	3	4	5
DRAKO	0	4	7	6	7
BYSON	0	7	16	2	6
KEANN	0	3	1	5	6
KIOWA	4	3	3	4	6

Table 9 - Conflict and TNAV Failure Summary

	PERCENT COMMERCIAL JET EQUIPAGE			
	25	50	75	100
(1) Total conflicts	14	13	11	8
(2) Total conflicts in freeze region	10	9	7	4
(3) Frozen, leading TNAV aircraft in conflict with unequipped	4	6	4	1
(4) Frozen, trailing TNAV aircraft in conflict with unequipped	2	2	2	1
(5) Conflict with two frozen TNAV aircraft	0	0	0	1
(6) Total arrivals	50	50	50	50
(7) TNAV arrivals	11	19	28	36
(8) Frozen TNAV arrivals involved in conflict	7	9	7	5
(9) Frozen TNAV arrivals in conflict (excluding TNAV leading)	2	2	2	2
(10) Ratio TNAV failures [(8) ÷ (7)]	.64	.47	.25	.14
(11) Ratio TNAV failures (excluding TNAV leading [(9) ÷ (7)]	.18	.11	.07	.06

Conflicts involving commuter/random high-performance aircraft are included in this table

Table 10 - Mix of Airplane Type, Equipage, and Simulation Time Period

Aircraft type	0%		25%		50%		75%		100%	
	4D equipped	un-equipped	4D equipped	un-equipped	4D equipped	un-equipped	4D equipped	un-equipped	4D equipped	un-equipped
727	0	23	6	17	13	10	18	5	23	0
737	0	8	1	7	2	6	5	3	8	0
767	0	5	4	1	4	1	5	0	5	0
Total	0	36	11	25	19	17	28	8	36	0
Period 3	0	3	0	3	0	3	3	0	3	0
Period 4	0	12	3	9	5	7	8	4	12	0
Period 5	0	21	8	13	14	7	17	4	21	0

APPENDIX A

DATA DICTIONARY

AAI = A/C acceptance interval

A/C DELAY = CLT-VTA for an individual A/C
= ACDLYLL

A/C ID = Airline ID + flight number

A/C LINK DATA = Forward link arrays + backward link arrays + ground hold headers

AIRCRAFT TIMES = Ground hold time + time at runway for ground hold A/C + time at the runway for LP A/C

AIRPORT DATA = Aircraft acceptance interval + last available runway time

AIRPORT STATISTICS = Throughput + utilization

ARAYEF = Indices in the entry fix list

ARRAY PARAMETERS = MXA + MXC + MXD + MXH + MXG + MXL + MXS + MXW

ARRIVAL METERING DATA = Time to meter fix for LP A/C + FCLT + FTUITIM

ARRIVAL METERING METER-FIX TIME = ATC-assigned time to cross the designated meter fix

ARRIVAL METERING POSITION DATA = Ground speed + reference waypoint + distance to reference waypoint + present altitude

ATC PARAMETERS = Delay control data + ATC separations

ATC SEPARATIONS = Lateral separation + vertical separation above 29000 ft + vertical separation below 29000 ft

ATC STATISTICS = Clearance statistics + conflict statistics + loading statistics

BADCLT FLAG = Reinitializes landing time calculations

CLEARANCE STATISTICS = Total number of clearances + number of 4D clearances

CLOCK TIME = Time of day based on 24-hr clock. Simulation proceeds incrementally based on clock time advances

APPENDIX A (continued)

CLT = Calculated landing time

CONFLICT DATA = Counts of conflicts + equipage of conflicting A/C + time of conflict + IDs of conflicting A/C

CONFLICT POSITION DATA = Reference waypoint + distance to reference waypoint + course + present altitude

CONFLICT STATISTICS = Number of conflicts + number of 4D conflicts

COUNTS = Number of HP A/C + number of commercial jets + number of 4D A/C + number of unequipped A/C + number of commuters + number of LP A/C

CURRENT A/C DATA = Ground hold times + surveillance position data + holding data + distance vector + ARAYEF + path ID + equipage of active A/C + A/C ID + time at meter fix + arrival metering meter fix time + speed reductions + freeze flag + A/C delay + ACIDLOW

DELAY CONTROL DATA = Delay control threshold times + velocity decrements

DELAY CONTROL THRESHOLD TIMES = Times which trigger path stretching and holding

DELAY DATA = Delay control data + delay control threshold times + delay parameters

DELAY PARAMETERS = A/C delay + cumulative A/C delay + number of processed A/C + total number of delayed A/C + delay of HP A/C + delay of LP A/C

ENTER ARRAY SIZES = MXA + MXD + MXL

ENTRY FIX TIMES = TEFIX

ENTRY POINT COUNT = Count of A/C using each entry point

EXITING A/C DATA = Number of exiting A/C + equipage of exiting A/C + types of exiting A/C + meter-fix accuracy of exiting A/C + fuel usage by exiting A/C

EXIT DATA = Number of active A/C + ARAYEF + ground hold times + surveillance position data + path ID + equipage + ACID + stack positions + stack numbers + time at the meter fix + speed

EXPERIMENT PARAMETERS = Times + write switches + metering flags + airport data + arrival metering data + ATC parameters + statistical parameters + traffic input file number

APPENDIX A (continued)

FLIGHT INFORMATION = Flight ID + A/C type + entry fix name + arrival time + departure time + flight time + metering eligibility + gross weight + cruise altitude + cruise speed + cruise Mach + equipage + DISTI

FORWARD LINK ARRAYS = HP forward link array + LP forward link array

FREEZE FLAG = Flag to show that an A/C is frozen

FREEZE LIST DATA = Freeze list time + freeze list A/C type

FREEZE LIST POINTER LIST = Pointers to HP and LP A/C data arrays

FREEZE LIST RUNWAY = Runway assigned to frozen A/C

FRZ FLAG = Flag to show that the VTA of an A/C is within FCLT minutes of clock time

FRZREG FLAG = Flag to show that an A/C is in the freeze region

FUEL USAGE = Total fuel by commercial jets + average and S. D. fuel by commercial jets + average and S. D. fuel by 4 D A/C + average and S. D. fuel by unequipped A/C

GH LINK DATA = Head of HP GH linked list + head of LP GH linked list

GH LIST DATA = ID of GH A/C + NOGH + expected time at runway

GHOLD FLAG = Flag to show that an A/C has been switched from ground hold to active status

GROUND-HOLD DATA = Ground hold time + number of ground hold A/C + ground hold flag

GROUND HOLD STATISTICS = Number of GH A/C in expanded metering + number of GH A/C in internal metering + cumulative minutes in expanded metering + cumulative minutes in internal metering

GROUND HOLD TIMES = GRHLD + AGRHLD + GHLOW

GROUND HOLD TIME WINDOW = DELTF

HEAD DATA = Header for HP linked list + header for LP linked list + header for HP GH linked list + header for LP GH linked list

HOLDING DATA = Stack entry altitude + stack exit altitude + stack exit time + stack airspeed

HP A/C ID = List of IDs of HP (high-performance—commercial, commuter, random high) A/C

APPENDIX A (continued)

HP LINK DATA = HP forward link array + HP backward link array + head of the HP linked list

HP ARRIVAL METERING DATA = ID GH A/C + ground hold time + time at runway + type of A/C + ACID

HP LIST DATA = HP links + HP backlink + header for HP list + header for GH list + HP ID list + A/C ID list

ID GH A/C = Input list of IDs of GH A/C

INDEPENDENT VARIABLES = AAI + FCLT + FTUITIM + percent equipage

LART = LAST AVAILABLE RUNWAY TIME

LINK DATA = HP link data + LP link data + GH link data

LIST DATA = Numbers of A/C + array EF + aircraft times + present position data + link data + A/C IDs

LOADING STATISTICS = Meter-fix loading + route loading + total route loading

LP A/C ID = List of IDs of LP A/C

LPFRZ FLAG = Flag to show that an LP A/C is frozen

LP ARRIVAL METERING DATA = ACID + time at runway + ground hold time

LP GH HEADER = Pointer to first GH LP A/C in LP linked list

LP LINK DATA = LP forward link array + LP backward link array + head of the LP linked list

LP LIST DATA = NOLO + NOPRVLO + LP A/C ID + expected time at the runway + duration of LP ground hold

MAP DATA = Clock time + number of active aircraft + entry point number + waypoint number + distance to next waypoint + present position altitude + plotting symbol selection number

MAPPING NUMBERS = Entry point number + waypoint number + plotting symbol selection number

APPENDIX A (continued)

METER-FIX ACCURACY = Average and S. D. of meter-fix accuracy for
(1) All HP A/C
(2) Commercial jets
(3) 4D A/C
(4) Unequipped A/C
(5) Commuter A/C

METER-FIX COUNT = Counts of A/C over each meter fix

METER-FIX COUNTERS = Counter for each meter fix + Cumulative count up to the beginning of each meter-fix list

METER-FIX DATA = Meter-fix name + meter-fix time

METER-FIX NAME = Five letter word representing a specific fix

METER-FIX POINTER LIST = Pointers to HP A/C data arrays

METERING FLAGS = Internal metering flag + expanded metering flag

METERING LIST DATA = Meter-fix data + outer fix data

MFT = Meter-fix time

NALT = Next available landing time

NEWFRZ FLAG = Flag to show that an A/C is newly frozen

NOGH = Number of GH A/C in this iteration

NOMTMF = Time decrement from VTA of LP A/C used to determine time for exit from simulation

NOPRVGH = Number of GH A/C in the previous iteration

NTOTGH = Total number of GH A/C which have been processed

NTOTLP = Total number of LP A/C which have been processed

NUMBER OF PLANES OVER THE ENTRY POINT

NUMBERS OF A/C = NOAA + NONEW + NOGH + NOPRVGH + NOLOW + NOPRVLO

NUMBERS OF ACTIVE A/C = NOAA + NONEW + NOLOW

APPENDIX A (continued)

NUMBERS OF CURRENT A/C = NOAA + NONEW + NOGH + NOLOW

NUMBERS OF EXITING A/C = Number of exiting HP A/C + number of exiting LP A/C
= NHPTHR + NLPTHR

NUMBERS OF PROCESSED A/C = NTOTHP + NTOTLP + NTOTGH

OUTER FIX DATA = Outer fix name + outer fix time

PATH = Number of segments + number of waypoints + segment distances + ID of each waypoint

PERCENT EQUIPAGE = Percentage of HP A/C equipped for 4D operation

POINTERS TO DEMAND LIST = INDDL

POLL DATA = Priority-ordered landing list data

PRESENT POSITION DATA = Path ID + reference waypoint + distance to reference waypoint + ground speed + predicted time at next fix + predicted time at waypoints array

PRIORITY-ORDERED LANDING LIST DATA = Priority-ordered list of links to the HP and LP linked lists + count of each priority + cumulative count up to the beginning of this priority + prioritized landing time + performance type

PRIORITY-DETERMINING FLAGS = FRZ flag + GHOLD flag

RUNWAY DATA = Last available runway time + aircraft acceptance interval

SPEED REDUCTIONS = VATC

STACK DATA = Stack positions + stack numbers + numbers in each stack

STATISTICAL PARAMETERS = Number of statistical sampling periods + starting time + stopping time

STATISTICAL PERIOD DATA = Period ID + period times

STATISTICS = Counts + meter fix accuracies + fuel usage + airport statistics + ATC statistics

SURVEILLANCE ARRAY SIZES = MXA + MXH + MXS + MXW

SURVEILLANCE POSITION DATA = Present altitude + ground speed + distance to reference waypoint + course + reference waypoint

APPENDIX A (continued)

TIMES = Clock step + simulation start time + duration of simulation

TIMES FOR ATC = Clock time + clock step

TRAFFIC INPUT FILE NUMBER = OAG data file

TRANSITION TIME = Time to fly from the meter fix to the runway at the adapted speed schedule

VECTORING DISTANCE = DISVEC

VTA = Vertex time of arrival

WAYPOINT NUMBERS = Number of starting waypoint + number of last waypoint + number of present waypoint

WRITE SWITCHES = IFLO + JFLO + KFLO

APPENDIX B

DENVER CENTER ROUTE DATA BASE

Entry point no.	Origin(s)	Metering fix	Dist. to MF(nmi)	Cruise alt. (FL) 707	727	737	767	Bus.[a] Jet
1	YEG—Edmonton	Drako	386	370	370	330	370	290
	YYC—Calgary			370	370	330	370	290
2	GEG—Spokane	Drako	290	370	370	330	370	290
3	BOI—Boise	Drako	298	370	370	330	370	290
	EUG—Eugene			370	370	330	370	290
	IDA—Idaho Falls							
	PDX—Portland			370	370	330	370	290
	SEA—Seattle			370	370	330	370	290
4	RNO—Reno	Drako	358	370	370	330	370	290
5	OAK—Oakland	Byson	426	370	370	330	370	290
	SFO—San Francisco			370	370	330	370	290
	SJC—San Jose			370	370	330	370	290
	SMF—Sacramento			370	370	330	370	290
6	FAT—Fresno	Byson	426	370	370	330	370	290
	MRY—Monterey			370	370	330	370	290
7	BUR—Burbank	Byson	448	370	370	330	370	290
	LAS—Las Vegas			370	370	330	370	290
	LAX—Los Angeles			370	370	330	370	290
	ONT—Ontario			370	370	330	370	290
	SBA—Santa Barbara			370	370	330	370	290
8	SAN—San Diego	Byson	515	370	370	330	370	290
9	PHX—Phoenix	Byson	412	370	370	330	370	290
	TUS—Tucson			370	370	330	370	290
10	ELP—El Paso	Byson	318	370	370	330	370	290
	MZT—Mazatlan			370	370	330	370	290
11	MAF—Midland	Kiowa	297	350	350	350	390	280
	SAT—San Antonio			350	350	350	390	280

[a]Commuter/random high-performance

APPENDIX B (continued)

Entry point no.	Origin(s)	Metering fix	Dist. to MF(nmi)	Cruise alt. (FL) 707	727	737	767	Bus.[a] Jet
12	DFW—Dallas-Ft. Wth.	Kiowa	285	350	350	350	390	280
	HOU—Houston			350	350	350	390	280
	IAH—Houston Int.			350	350	350	390	280
	MSY—New Orleans			350	350	350	390	280
13	LIT—Little Rock	Kiowa	284	350	350	350	390	280
	MEM—Memphis			350	350	350	390	280
	OKC—Oklahoma City			350	350	350	390	280
14	ATL—Atlanta	Kiowa	284	390	390	350	390	310
	BHM—Birmingham			390	390	350	390	310
	BNA—Nashville			350	350	350	390	280
	MIA—Miami			390	390	350	390	310
	TPA—Tampa			390	390	350	390	310
	TUL—Tulsa			350	350	350	390	280
15	ICT—Wichita	Kiowa	284	350	350	350	390	280
	SGF—Springfield			350	350	350	390	280
16	IND—Indianapolis	Kiowa	363	350	350	350	390	280
	MCI—Kansas City			350	350	350	390	280
	SDF—Louisville			350	350	350	390	280
	STL—St. Louis			350	350	350	390	280
17	JAC—Jackson	Drako	265	330	330	330	370	270
	WYS—West Yel.			330	330	330	370	270
18	BWI—Baltimore	Keann	401	390	390	350	390	310
	CAK—Akron			390	390	350	390	310
	CLE—Cleveland			390	390	350	390	310
	CMH—Columbis			390	390	350	390	310
	DAY—Dayton			390	390	350	390	310
	DMS—Des Moines			350	350	350	390	280
	EWR—Newark			390	390	350	390	310
	FWA—Ft. Wayne			350	350	350	390	280
	IAD—Wash., D.C.			390	390	350	390	310
	JFK—N. Y. (JFK)			390	390	350	390	310
	MLI—Moline			350	350	350	390	280
	ORD—Chicago			350	350	350	390	280
	PIA—Peoria			350	350	350	390	280
	PIT—Pittsburgh			390	390	350	390	310

[a]Commuter/random high-performance

APPENDIX B (continued)

Entry point no.	Origin(s)	Metering fix	Dist. to MF(nmi)	Cruise alt. (FL) 707	727	737	767	Bus.[a] Jet
	PHL—Philadelphia			390	390	350	390	310
	SBN—South Bend			350	350	350	390	280
	TOL—Toledo			390	390	350	390	310
	CID—Cedar Rapids			350	350	350	390	280
19	ALO—Waterloo, Iowa	Keann	401	350	350	350	390	280
	DTW—Detroit			350	350	350	390	280
	FNT—Flint			350	350	350	390	280
	GRR—Grand Rapids			350	350	350	390	280
	MBS—Saginaw			350	350	350	390	280
20	BOS—Boston	Keann	422	390	390	350	390	310
	MKE—Milwaukee			350	350	350	390	280
21	MSP—Minneapolis	Keann	422	350	350	350	390	280
22	FAR—Fargo	Keann	469	350	350	350	390	280
23	ABQ—Albuquerque	Byson	272	370	330	330	370	290
24	ALS—Alamosa	Byson	126	290	290	290	290	230
25	AMA—Amarillo	Kiowa	298	350	350	350	390	280
26	ASE—Aspen	Byson	71	170	170	170	170	170
27	BFF—Scotts Bluff	Keann	120	260	260	260	260	260
28	BIL—Billings	Keann	366	370	330	330	370	290
29	BIS—Bismarck, N.D.	Keann	461	350	350	350	390	280
30	CIG—Craig	Drako	111	250	250	250	250	250
31	CNE—Canon City	Byson	65	170	170	170	170	170
32	COD—Cody	Drako	310	370	370	330	370	290
33	COS—Colorado Springs	Kiowa	33	100	100	100	100	100

[a]Commuter/random high-performance

APPENDIX B (continued)

Entry point no.	Origin(s)	Metering fix	Dist. to MF(nmi)	Cruise alt. (FL) 707	727	737	767	Bus.[a] Jet
34	CPR—Casper	Drako	178	330	330	330	370	270
35	CSE—Crested Butte	Byson	77	190	190	190	190	190
36	CYS—Cheyenne	Drako	92	200	200	200	200	180
37	DRO—Durango	Byson	160	330	330	330	330	270
38	FMN—Farmington	Byson	192	350	350	350	390	280
39	FSD—Sioux Falls	Keann	385	350	350	350	390	280
40	FTC—Ft. Collins	Drako	43	110	110	110	110	110
41	GCC—Gillette	Drako	260	370	370	330	370	290
42	GCK—Garden City	Kiowa	197	350	350	350	390	280
43	GJT—Grand Junction	Byson	149	290	330	290	330	270
44	GLD—Goodland	Kiowa	142	280	280	280	310	260
45	GUC—Gunnison	Byson	76	190	190	190	190	190
46	HDN—Steamboat Springs	Drako	80	190	190	190	190	190
47	HYS—Hays, Kansas	Kiowa	254	350	350	350	390	280
48	LAA—Lamar	Kiowa	107	240	240	240	240	240
49	LAR—Laramie	Drako	68	170	170	170	170	170
50	LBF—North Platte	Keann	176	350	350	350	350	280
51	LBL—Liberal	Kiowa	214	350	350	350	390	280
52	LNK—Lincoln	Keann	353	350	350	350	390	280
53	LXV—Leadville	Byson	43	110	110	110	110	110

[a]Commuter/random high-performance

APPENDIX B (concluded)

Entry point no.	Origin(s)	Metering fix	Dist. to MF(nmi)	Cruise alt. (FL) 707	727	737	767	Bus.[a] Jet
54	MCK—McCook	Kiowa	212	350	350	310	350	280
55	MTJ—Montrose	Byson	116	250	250	250	250	250
56	OMA—Omaha	Keann	396	350	350	350	390	280
57	PUB—Pueblo	Kiowa	69	160	160	160	160	160
58	RAP—Rapid City	Keann	247	390	390	350	390	310
59	RIW—Riverton	Drako	233	370	370	330	370	290
60	RKS—Rock Springs	Drako	202	370	370	330	370	290
61	RWL—Rawlins	Drako	142	290	290	290	330	270
62	SBS—Steamboat Springs	Drako	77	190	190	190	190	190
63	SHR—Sheridan	Drako	290	370	370	220	370	290
64	SLC—Salt Lake City	Drako	314	370	370	330	370	290
65	SLT—Salida	Byson	57	150	150	150	150	150
66	SNY—Sidney	Keann	92	220	220	220	220	220
67	STK-Sterling	Keann	55	140	140	140	140	140
68	SUX—Sioux City	Keann	380	390	390	350	390	310
69	WHR—Vail	Byson	57	150	150	150	150	150
70	WRL—Worland	Drako	271	370	370	330	370	290

[a]Commuter/random high-performance

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16. Abstract

This document presents the results of an effort to estimate how often a TNAV (Time Navigation) equipped aircraft could be given a TNAV clearance in the En Route Metering (ERM) system as a function of the percentage of arriving traffic which is TNAV equipped. A fast-time simulation of Denver Stapleton International arrival traffic in the Denver Air Route Traffic Control Center route structure, including en route metering operations, was used to develop data on estimated conflicts, clearance communications and fuel usage for traffic mixes of 25, 50, 75 and 100% TNAV equipped. This study supports an overall effort by NASA to assess the benefits and required technology for using TNAV-equipped aircraft in the ERM environment.

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